APPENDIX M

ALTERNATIVE MODEL DOCUMENTATION

Rusk-Panola Attainment Demonstration State Implementation Plan for the 2010 Sulfur Dioxide National Ambient Air Quality Standard

Project Number 2020-057-SIP-NR
SFR-122/2020-057-SIP-NR

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APPENDIX M-1: LETTER TO THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Appendix M-1 includes a letter from Texas Commission on Environmental Quality (TCEQ) to the United States Environmental Protection Agency (EPA) requesting the use of the alternate model American Meteorological Society/EPA Regulatory Model – Highly Buoyant Plume (AERMOD-HBP). The letter and two attachments, Attachment 1: *AERMOD-HBP Formulation Documents from AECOM* and Attachment 2: *Modeling Protocol for Alternative Model Approval Demonstration for the Rusk-Panola Attainment Demonstration State Implementation Plan Revision for the 2010 Sulfur Dioxide (SO2) National Ambient Air Quality Standard*, was emailed by the TCEQ and to the EPA's Region Six office on May 24, 2021.

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Protecting Texas by Reducing and Preventing Pollution

May 24, 2021

David Garcia
Director, Air and Radiation Division
United States Environmental Protection Agency, Region 6
1201 Elm Street, Suite 500
Dallas, Texas 75270

Re: Request for Alternative Model Approval for the Rusk-Panola Attainment Demonstration (AD) State Implementation Plan (SIP) Revision for the 2010 Sulfur Dioxide (SO_2) National Ambient Air Quality Standard (NAAQS)

Dear Mr. Garcia:

The Texas Commission on Environmental Quality (TCEQ) requests that the United States Environmental Protection Agency (EPA) approve an alternative model for use in the Rusk-Panola 2010 SO_2 NAAQS AD SIP Revision, as provided by 40 Code of Federal Regulations (CFR) Part 51, Appendix W, Section 3.2.2(b)(2).

The TCEQ requests approval of American Meteorological Society/EPA Regulatory Model – Highly Buoyant Plume (AERMOD-HBP) as the alternative model. AERMOD-HBP is an alternative formulation of the EPA's preferred model, AERMOD (40 CFR Part 51, Appendix W, Section 4.2.2.1), in which the penetrated plume component has been modified. AERMOD-HBP was developed by AECOM and its formulation is described in Attachment 1: *AERMOD-HBP Formulation Documents from AECOM*.

The TCEQ contracted with Ramboll US Consulting, Inc. to perform a model performance evaluation of both AERMOD and AERMOD-HBP using evaluation procedures recommended in 40 CFR Part 51, Appendix W, Section 3.2. Details of the evaluation techniques used to support the request for AERMOD-HBP's alternative model approval are provided in Attachment 2*: Modeling Protocol for Alternative Model Approval Demonstration for the Rusk-Panola Attainment Demonstration State Implementation Plan Revision for the 2010 Sulfur Dioxide (SO_2) National Ambient Air Quality Standard*.

The TCEQ's statistical performance evaluation comparing modeled and monitored data shows that AERMOD-HBP performs better in estimating SO_2 concentration distributions at monitors in and near the Rusk-Panola nonattainment area. This supports approval of AERMOD-HBP as an alternative model for use in the Rusk-Panola 2010 SO_2 NAAQS AD SIP Revision.

If you have questions or need additional information, please contact Donna F. Huff, Deputy Director of the Air Quality Division, at (512) 239-6628 or Donna.Huff@tceq.texas.gov.

Sincerely,

Tonya Baer, Director
Office of Air
Texas Commission on Environmental Quality

Enclosures:
Attachment 1: *Formulation Documentation of AERMOD-HBP from AECOM*
Attachment 2: *Modeling Protocol for Alternative Model Approval Demonstration for Attainment Demonstration State Implementation Plan Revision for the 2010 Sulfur Dioxide (SO_2) National Ambient Air Quality Standard*

cc: Guy Donaldson, EPA Region 6, U.S. Environmental Protection Agency
Erik Snyder, EPA Region 6, U.S. Environmental Protection Agency

ATTACHMENT 1

AERMOD-HBP FORMULATION DOCUMENTS FROM AECOM

LIST OF DOCUMENTS

Paine, R., Szembek, C., and Warren, C., May 19, 2021, *Discussion of Penetrated Plume Treatment in AERMOD – Recommended Highly Buoyant Plume (HBP) Improvements*, AECOM

Model Evaluation Results for Baldwin and Labadie, Appendix A to Paine *et al.*, (2021)

Baldwin Table and Plots, Appendix B to Paine *et al.*, (2021)

Labadie Tables and Plots, Appendix C to Paine *et al.*, (2021)

Weil, J. C., Corio, L. A., and Brower, R. P., 1997, A *PDF Dispersion Model for Buoyant Plumes in the Convective Boundary Layer*, Journal of Applied Meteorology. 36, 982-1003

Moore, G.E., Milich, L.B., Liu M.K., 1988, *Plume behaviors observed using lidar and SF6 tracer at a flat and hilly site*, Atmospheric Environment, Volume 22, Issue 8, 1988, Pages 1673-1688

Weil, J. C., January 2, 2020, *New Dispersion Model for Highly-Buoyant Plumes in the Convective Boundary Layer*, Preliminary Draft v4.

Szembek, C., M. Garrison, and R. Paine, 2017, *DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD Black Box*, A&WMA Annual Conference, June 6, 2017

Presentation by Dr. Ken Rayner on February 25, 2013, *Review of models for dispersion of tall stack plumes at Collie.* Provided to Robert Paine of AECOM on 2/25/2013, and later to Roger Brode of USEPA's Office of Air Quality Planning and Standards on June 11, 2014

Warren, C., R. Paine, and J. Connors, 2019, *Evaluation of AERMOD SO2 Predictions for a Research-Grade Field Experiment*, Paper MO10, presented at the Air & Waste Management Association specialty conference (Guideline on Air Quality Models: Planning Ahead), March 19-21, 2019. Durham, NC

Discussion of Penetrated Plume Treatment in AERMOD – Recommended Highly Buoyant Plume (HBP) Improvements

Robert Paine, Carlos Szembek, and Christopher Warren, AECOM

May 19, 2021

Overview of Issue

In convective conditions, AERMOD has a three-plume treatment for stack emissions: direct, indirect and penetrated components (**Figure 1, *Three-plume Treatment by AERMOD in Convective Conditions***). For any given hour, the plume mass can be divided into as many as all three of these plume cases. As shown in **Figure 1**, the direct and indirect plumes remain within the convective mixed layer, which features vigorous vertical mixing above the surface layer (the lowest ~10% of the mixed layer). The penetrated plume is the portion of the plume that is sufficiently buoyant to break through the elevated inversion into the stable layer aloft. In this stable layer, the vertical turbulence is much lower than it is in the convective mixed layer, and the penetrated plume is observed to remain in that layer until late morning/early afternoon when the convective mixing height rises to intercept the plume due to diurnal heating. This document discusses how the current AERMOD formulation does not treat the dynamics of the penetrated plume correctly. In certain cases, AERMOD models a penetrated plume as mixing into the convective layer well before the convective mixed layer rises to the plume level. The authors propose an alternative approach, developed in conjunction with Dr. Jeffrey Weil,[1] that provides a more reasonable treatment of the penetrated plume. Discussions of similar findings in other databases and studies conducted by other investigators are also provided.

Behavior of the Penetrated Plume

Dr. Weil has studied the issue of the penetrated plume for decades. A peer-reviewed paper[2] (provided as **Attachment 1**) that he co-authored notes that the penetrated plume rises into the stable layer above the convective boundary layer and is subsequently mixed to the ground only when the convective mixing height rises to intercept it. A conceptual diagram of the nature of the penetrated plume from the Weil et al. (1997) paper as shown in **Figure 2, *Depiction of Penetrated Plume Aloft*** , indicate that the penetrated plume mixes to the ground over time, yet not necessarily during the same hour that it is emitted into the stable layer aloft.

Research-grade experiments in the 1980s were able to detect plume concentrations aloft using laser imaging, detection, and ranging (“LIDAR”) instrumentation. The methods used for the EPRI Kincaid and Bull Run field studies are described by Moore et al. (1988)[3] and are provided as **Attachment 2**. Remote-

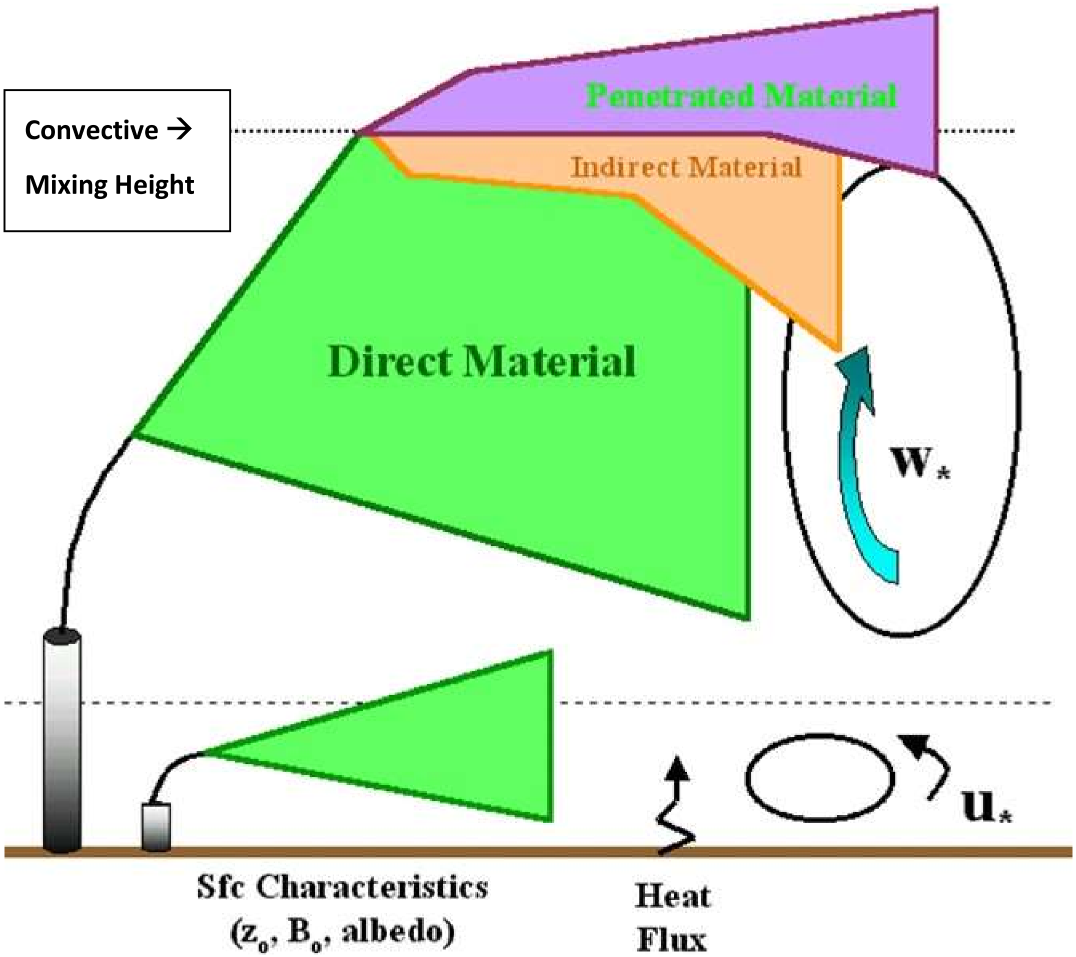
[1] Dr. Weil and Robert Paine (one of the AECOM authors of this document) were members of the AERMOD development team.

[2] Weil, J. C., Corio, L. A., and Brower, R. P.: 1997, 'A PDF Dispersion Model for Buoyant Plumes in the Convective Boundary Layer', *J. Appl. Meteorol*. 36, 982-1003.

[3] G.E. Moore, L.B. Milich, M.K. Liu, 1988. Plume behaviors observed using lidar and SF6 tracer at a flat and hilly site, *Atmospheric Environment*, Volume 22, Issue 8, 1988, Pages 1673-1688, ISSN 0004-6981,

sensing observations of the plume aloft were made by ground-based, mobile sulfur dioxide (SO_2), differential adsorption LIDAR ("DIAL"), ground-based, mobile particle-sensing LIDAR, and airplane-based particle LIDAR known as an airborne LIDAR plume and haze analyzer ("ALPHA-l"). The SO_2 DIAL instrument measured the absolute SO_2 concentrations of the plume aloft. For the LIDAR to observe the entire plume cross-section, it had to be operated within 2 km of the stack at Kincaid and within 1 km at Bull Run. The ground-based LIDARs scanned the plume through a plane normal to the plume centerline aloft and through a plane parallel to the ground-level concentration pattern.

Figure 1: Three-plume Treatment by AERMOD in Convective Conditions



Inversion heights associated with the convective mixed layer height for the Kincaid and Bull Run field studies were determined throughout the daytime period from frequent tethersonde[4] soundings. Vertical plume cross sections were determined from the remote sensing measurements, and plume concentrations in parts per billion (ppb) were mapped for several hourly averaging periods.

Figures 3 through **6, *LIDAR Images From Bull Run,*** show an example of the time evolution of the plume behavior during one morning at Bull Run up to the time that the convective mixing height (marked in red in each figure) intercepted the plume aloft. The figures, which cover four separate hours for that day,

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https://doi.org/10.1016/0004-6981(88)90396-4.

[4] A tethersonde is a radiosonde attached to a fixed or tethered balloon.

show the integrated plume concentration in the X-Z plane. Basically, the compact nature of the plume was preserved until the noon hour (the last in the series, **Figure 6**) when the convective mixing height finally rose through the layer occupied by the plume. This behavior shows that prior to this time, the penetrated plume remained above the mixing height and did not mix down to the ground until it was intercepted by the rising convective mixed layer. The maximum ground-level concentrations for this case were about four times higher during the hour 1200-1300 than the preceding hours that day. The plume centerline concentrations aloft were about a factor of four lower after mixing throughout the convective boundary layer.

Figure 2: Depiction of Penetrated Plume Aloft by Weil et al., 1997

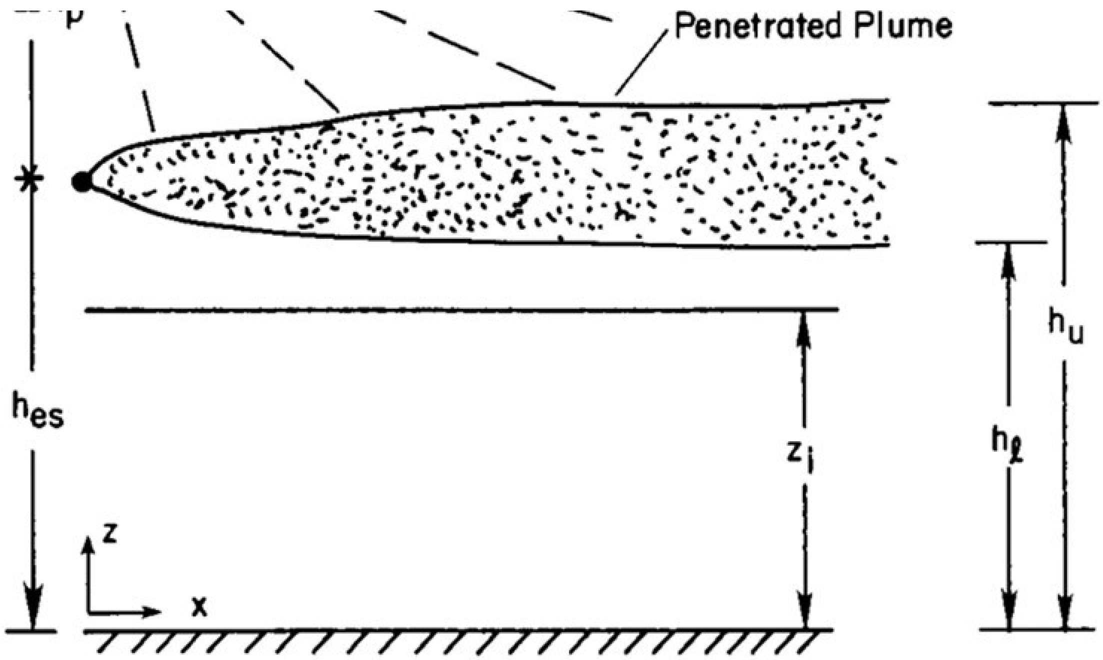


Figure 3: Lidar Image from Bull Run, October 4, 1982, 8-9 AM

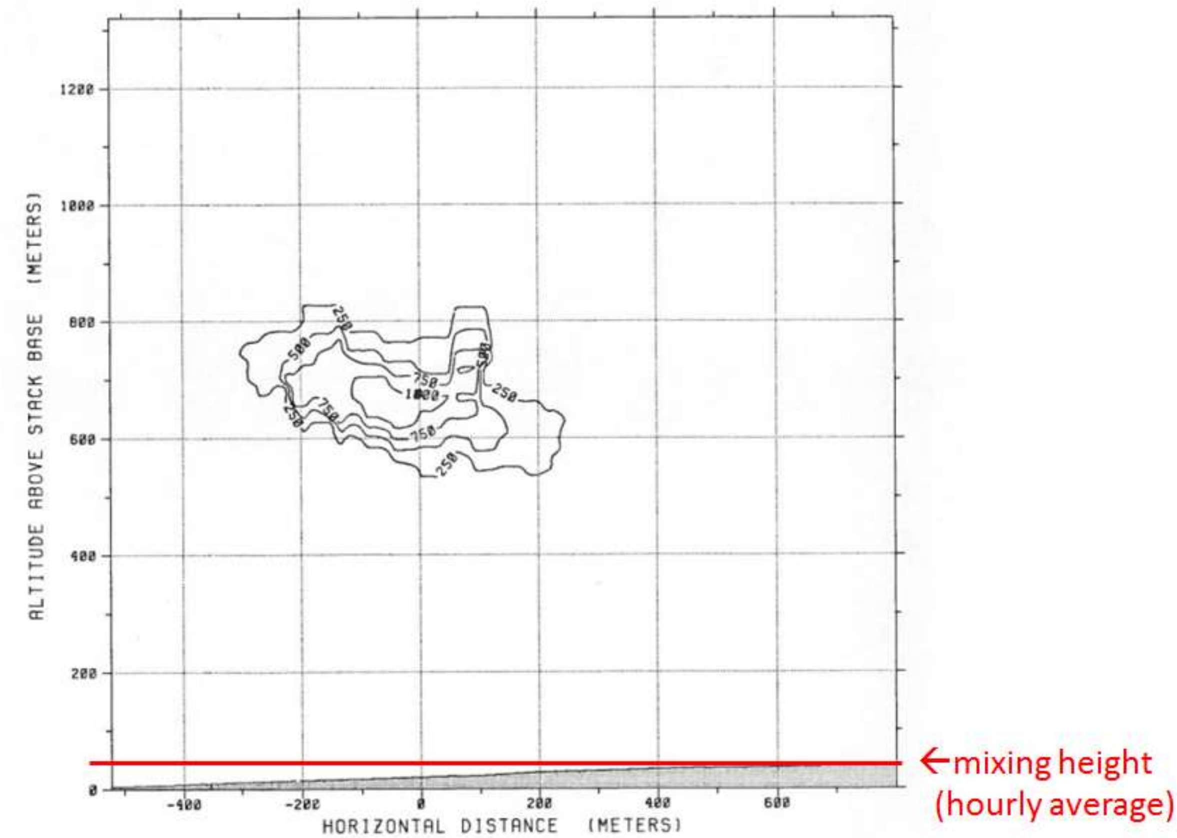


Figure 4: Lidar Images from Bull Run, October 4, 1982, 10-11 AM

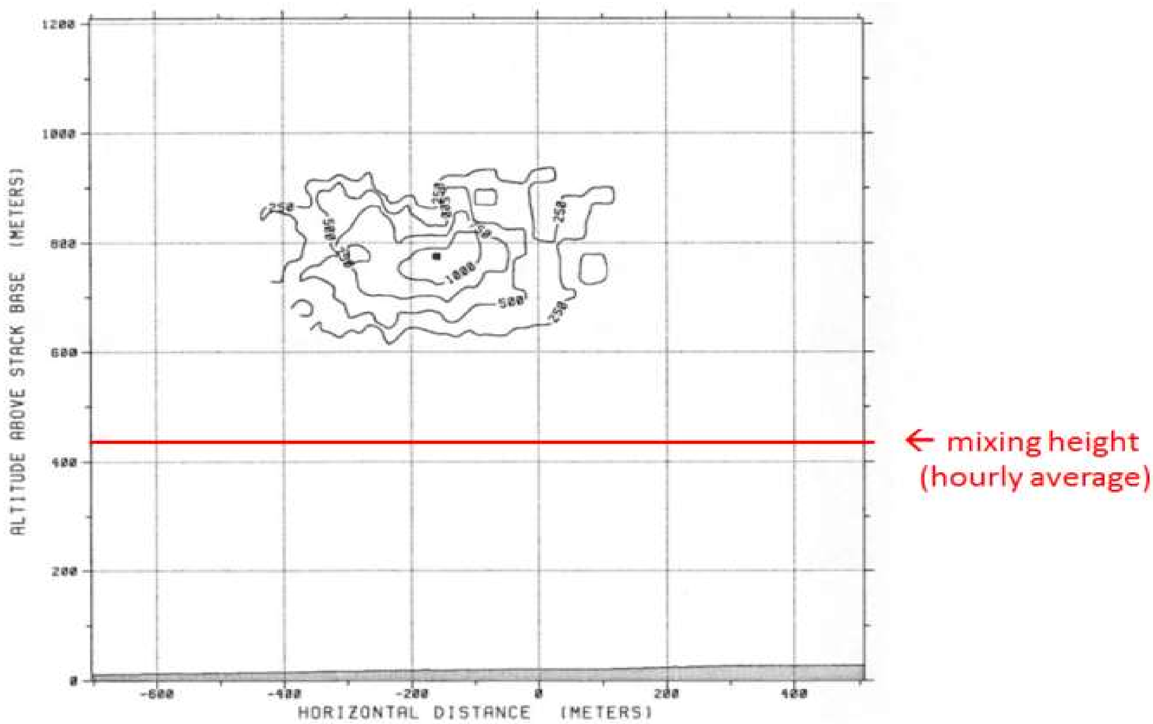


Figure 5: Lidar Image from Bull Run, October 4, 1982, 11 AM - noon

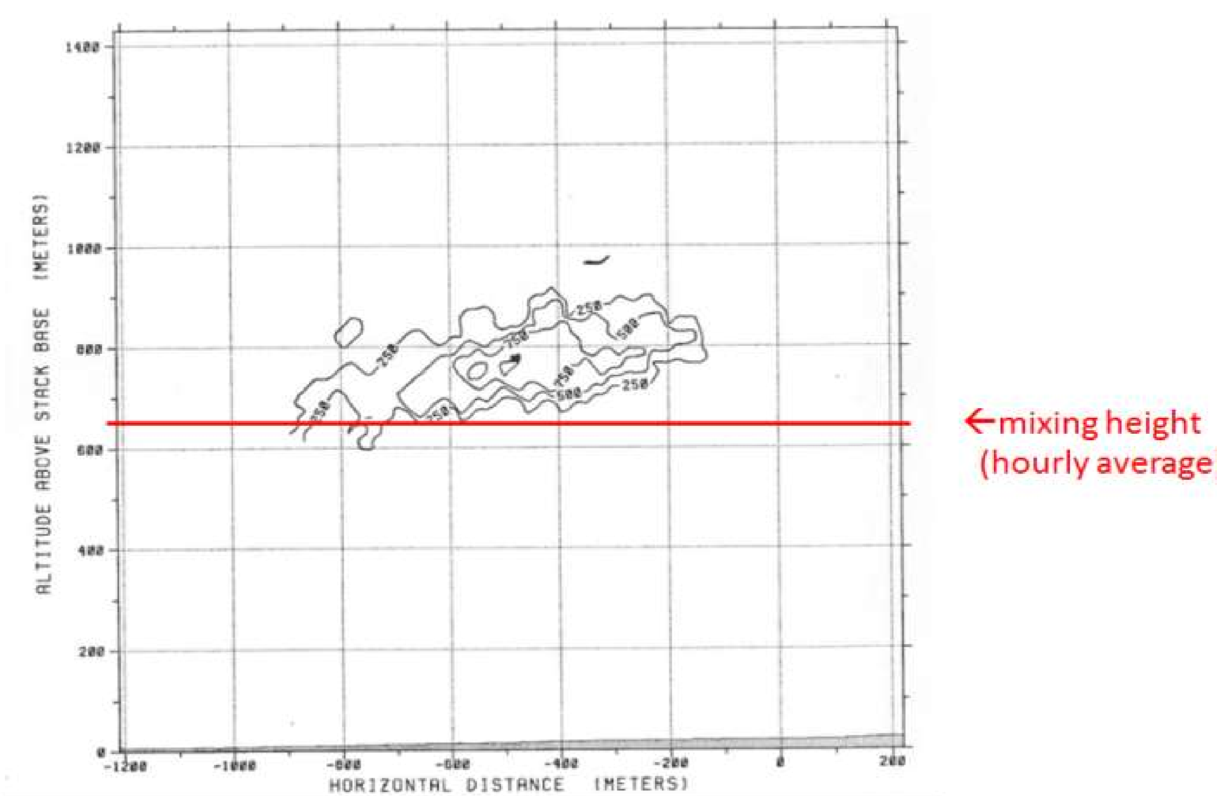
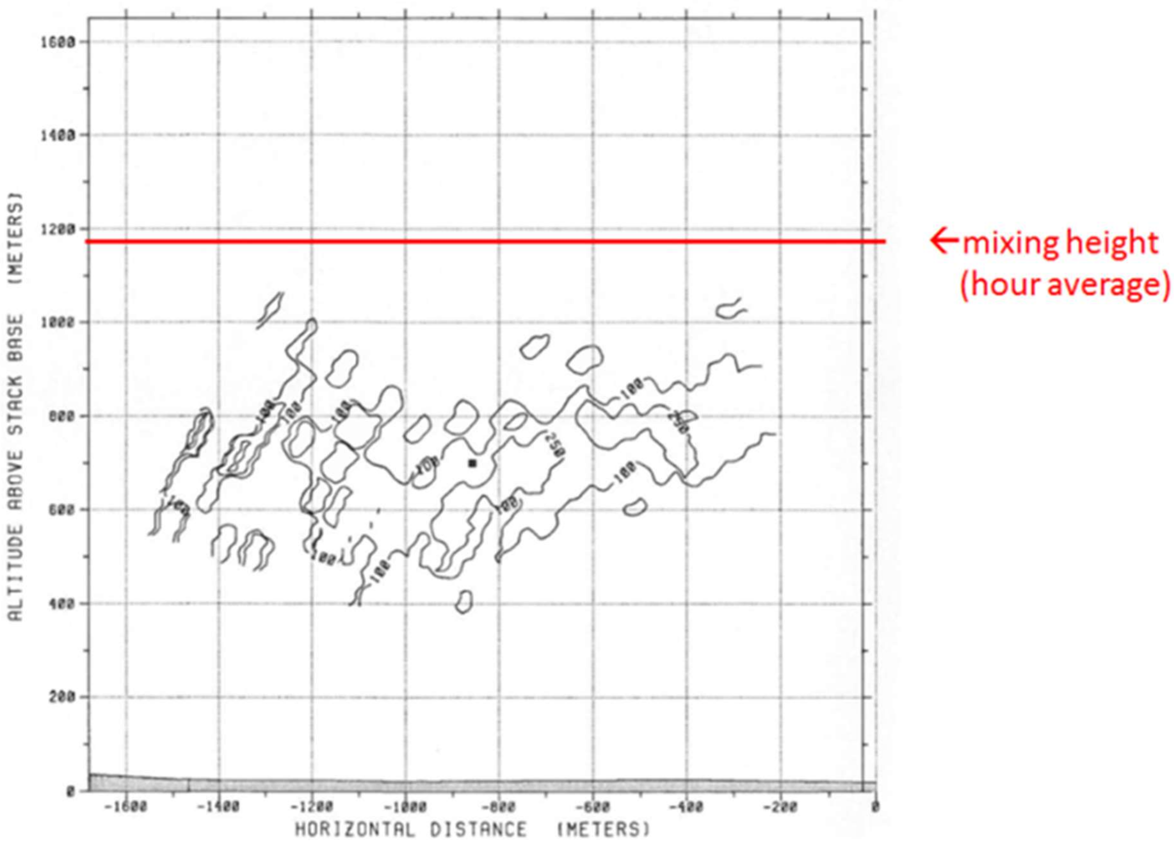


Figure 6: Lidar Image from Bull Run, October 4, 1982, noon – 1 PM



Based upon the findings noted above, the likelihood of elevated ground-level concentrations resulting from a penetrated plume is low until the convective mixed layer has risen to intercept the plume. The penetrated plume interception event, often referred to as "daytime fumigation," typically leads to elevated concentrations only during a single hour of the day. The multiple-hour evolution of this process, as shown in Figures 3-6, presents a challenge because AERMOD is a steady-state model and has no information, absent the proposed enhancements discussed below, of the next hour's conditions.

Current Implementation in AERMOD

AERMOD version 21112 currently results in the mixing of the penetrated plume into the convective boundary layer during more hours than expected, resulting in a premature and repetitious mixing of the penetrated plume to the ground that only occurs once during the daytime hours. Because this premature mixing assumption is repeated for multiple hours leading up to the actual interception of the penetrated plume by the rising convective boundary layer ("CBL"), AERMOD will overstate the frequency of the plume mixing events, resulting in overpredictions. This issue with AERMOD has been observed by investigators associated with field studies where the model is found to overpredict ground-level concentration events due to the penetrated plume issue and make those predictions too often and too early, by as much as 2-4 hours, in the day compared to the timing of observed ground-level impacts.

A key area of scrutiny in the AERMOD formulation is the parameterization of the penetrated plume's vertical spreading through its calculation of "effective" dispersion parameters. AERMOD's formulation computes vertically-integrated values between the plume centerline and the higher level of the plume's bottom edge and receptor at the ground. However, this calculation can substantially overstate the vertical plume growth if the wrong vertical plume depth (a function of vertical plume dispersion, sigma-z) is assumed by the model.

The central issue for the penetrated plume handling in AERMOD is that the computation of sigma-z (used to determine the plume's bottom edge) is a function of the stability in the layer occupied by the plume. By definition, the penetrated plume is in a stable layer above the mixing height, but the AERMOD formulation assumes a neutral layer for computing the penetrated plume sigma-z, which substantially and incorrectly increases the sigma-z value. This formulation, according to the AERMOD model formulation document,[5] assumes that the penetrated plume mixes into the CBL and thus encounters a non-stable layer for the portion of the plume that reaches the ground. However, this assumption is only correct if the mixing height rises fast enough to capture at least a portion of the penetrated plume by the end of the current hour, according to Weil et al. 1997.[2] Otherwise, this assumption is incorrect as evidenced by the direct observations of the actual penetrated plume behavior not mixing down from the stable layer aloft while the CBL remains below the plume.

AERMOD computes the "effective" values for turbulence parameters (vertical turbulence, sigma-w in particular) that involves averaging through a vertical depth between the plume centerline to the bottom of the plume, which is a distance of 2.15 sigma-z below the plume centerline. With the incorrect assumption of a large sigma-z for a penetrated plume, AERMOD averages sigma-w over a depth that, in reality, can involve large changes in sigma-w with height above the mixing height (see **Figure 7, *AERMOD's Treatment of Vertical Turbulence in Convective Conditions***). Hence, for hours when the actual mixing height has yet to intercept the plume, the averaged, computed value does not represent local turbulence conditions at the penetrated plume's centerline height. For many cases, where the vertical integration occurs over a significant depth within the convective boundary layer, the modeled plume spreading will be greatly exaggerated because the actual values of sigma-w in the convective boundary layer can be an order of magnitude higher than those in the stable layer aloft.

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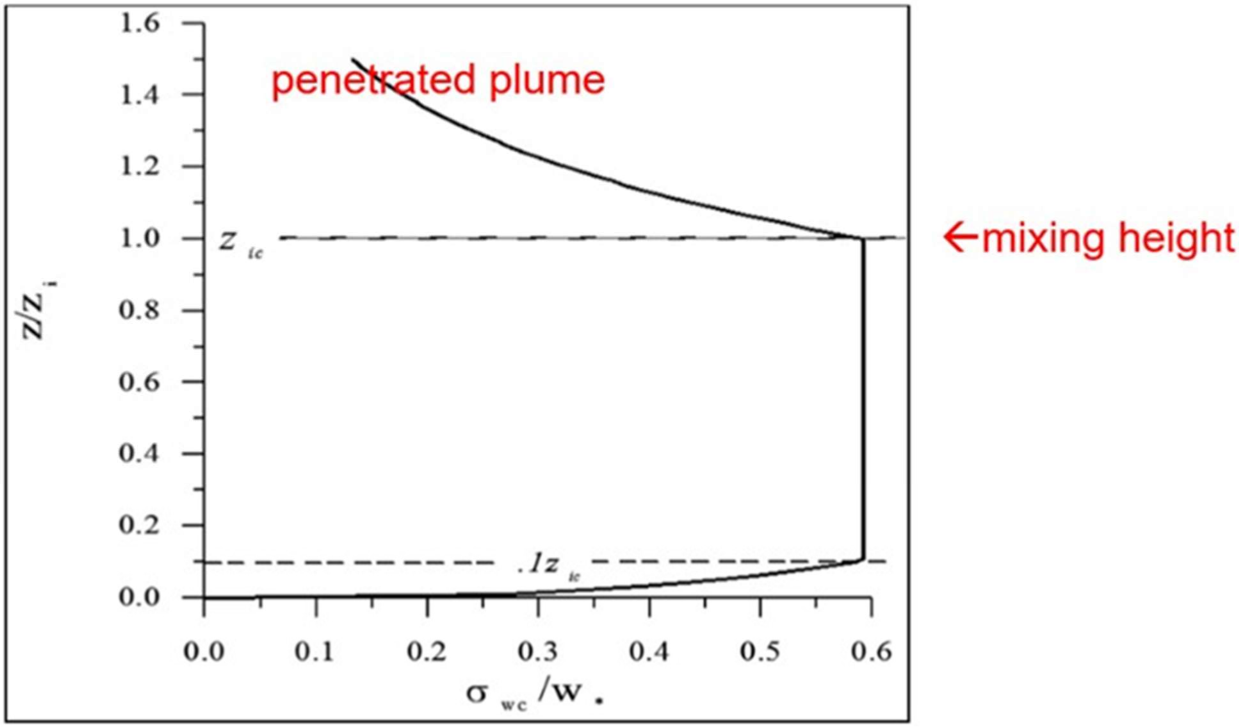
[5] EPA, 2019. AERMOD Model Formulation and Evaluation Document. Available at https://gaftp.epa.gov/Air/aqmg/SCRAM/models/preferred/aermod/aermod_mfed.pdf.

Figure 7: AERMOD's Treatment of Vertical Turbulence in Convective Conditions



Debugging of AERMOD to Understand the Penetrated Plume Issue

Due to AERMOD's three-plume treatment as shown in **Figure 1**, the findings noted above for the penetrated plume were not easy to diagnose. The "Model Debug" output from AERMOD is one way to review plume behavior in AERMOD, but the file size for the output is so large that its use is impractical for routine modeling applications. This awkward debug file issue led AECOM, with funding from EPRI, to develop a more streamlined "DISTANCE DEBUG" output that lists the coherent plume statistics for only the peak impact receptor for each source and each hour, thus resulting in a manageable output size that is still useful. This tool has been documented in a conference presentation[6] (provided as **Attachment 4**) as well as Texas Commission on Environmental Quality's (TCEQ's) submittal[7] to EPA in 2016 for Round 2 of the SO_2 National Ambient Air Quality Standard (NAAQS) implementation. The TCEQ submittal notes on page 162 of 269 that,

> *"the "DISTANCE DEBUG" output capability of AERMOD is documented and freely available from EPRI at https://sourceforge.net/projects/epri-dispersion/", and that the "review of Sierra Club modeling results for Martin Lake [relied upon by EPA for their nonattainment designation] that were re-run with a 'DISTANCE DEBUG' enhanced AERMOD debugging output confirms that the Martin Lake peak AERMOD-predicted concentrations are caused by the simulated penetrated plume."*

Two examples of how various debug output data available from AERMOD show the current problem with the penetrated plume are discussed in the following subsection.

Examples of Martin Lake Penetrated Plume Overprediction Issues

AERMOD modeling conducted with three years of data (2018-2020) shows that the model, using default options, overpredicts the 3-year design concentration (3-year average of the 99th percentile peak daily 1-hour maximum concentration) at the monitoring site by about 30%. This overprediction tendency would result in an initial 30% penalty for Martin Lake to show NAAQS compliance with a reduced emission rate. The cause of the overprediction has been determined to be the penetrated plume and the top ten AERMOD predictions are all dominated by the penetrated plume issue, as shown in the DISTANCE-DEBUG output (**Table 1, *Excerpts of DISTANCE-DEBUG Output for Top 10 Daily Maxima AERMOD Default Impacts at Martin Lake Creek Monitor***).

The combination of AERMOD's MODEL and METEOR debug files, in addition to the DISTANCE-DEBUG output files, were used to diagnose the penetrated plume issue with the default, regulatory-approved AERMOD model. Two specific Martin Lake events are discussed below, the first occurring on June 3, 2019, at hour 11 and the second on June 29, 2019, at hour 11.

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[6] Szembek, C., M. Garrison, and R. Paine, 2017. "DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD Black Box", A&WMA Annual Conference; Pittsburgh, PA; June 6, 2017.

[7] Available at https://www.tceq.texas.gov/assets/public/implementation/air/sip/so2/2015RevisedRecommendation/041916_SO2_Designation_120-Day_Response.pdf.

Table 1: Excerpts of DISTANCE-DEBUG Output for Top 10 Daily Maxima AERMOD Default Impacts at Martin Lake Creek Monitor

Daily Maxima RANK	YYMMDDHH	TOTAL Conc. (μg/m³)	u* (m/s)	w* (m/s)	OBULEN (m)	Z_{mech} (m)	Z_{conv} (m)	SFC Z_0 (m)	Source ID	Actual Emissions (g/s)	Ts (K)	Vs (m/s)	Final Plume Height (FPH) (m)	Distance to FPH (m)	WDIR @ FPH (deg.)	Effective Wind Speed (m/s)	Plume Type	Meander Fraction	Partial Penetration Fraction	Effective Sigma V (m/s)	Effective Sigma W (m/s)	Hourly Conc. (μg/m³)
1	18090609	666.1	0.14	0.74	-5.2	130	285	0.032	S1	*875.4*	*360.2*	*33.7*	445.5	924.9	77	1.9	PEN	0.177	1.000	0.51	0.36	210.3
									S2	*824.3*	*347.7*	*29.8*	419.3	924.9	77	1.8	PEN	0.179	0.969	0.51	0.38	218.9
									S3	*972.8*	*363.1*	*32.4*	445.6	924.9	77	1.9	PEN	0.177	1.000	0.51	0.36	221.8
2	20032213	619.2	0.14	0.67	-7.3	125	322	0.025	S1	*0.3*	*306.4*	*2.3*	238.8	307.6	80	2.0	IND	0.147	0.075	0.48	0.42	0.1
									S2	*1097.6*	*361.7*	*31.8*	418.9	1227.1	80	2.0	PEN	0.141	0.769	0.48	0.38	321.8
									S3	*920.6*	*347.7*	*29.1*	405.6	1227.1	80	2.0	PEN	0.142	0.714	0.48	0.38	282.2
3	18022211	604.5	0.20	0.49	-42.1	213	259	0.02	S1	*728.1*	*345.5*	*33.1*	324.5	1656.1	82	3.5	PEN	0.052	0.779	0.48	0.31	184.2
									S2	*866.0*	*362.0*	*33.4*	332.1	1791.4	82	3.5	PEN	0.052	0.820	0.48	0.31	221.8
									S3	*701.7*	*358.3*	*34.9*	332.4	1795.8	82	3.5	PEN	0.052	0.821	0.48	0.31	183.5
4	18101910	585.8	0.13	0.43	-11.9	117	186	0.027	S1	*507.0*	*361.2*	*28.8*	348.7	965.2	77	1.9	PEN	0.094	1.000	0.35	0.15	167.0
									S2	*585.2*	*348.1*	*27.2*	334.1	965.2	77	1.9	PEN	0.095	1.000	0.35	0.17	227.6
									S3	*469.4*	*346.8*	*26.9*	332.1	965.2	77	1.9	PEN	0.095	1.000	0.35	0.17	176.2
5	18123011	572.2	0.13	0.45	-19.3	114	317	0.02	S1	*946.6*	*346.2*	*32.4*	378.2	1692.4	74	2.1	PEN	0.082	0.609	0.37	0.28	233.2
									S2	*555.1*	*347.8*	*20.5*	362.6	1420.6	74	2.1	PEN	0.083	0.506	0.37	0.28	126.6
									S3	*998.6*	*343.3*	*31.9*	376.1	1657.1	74	2.1	PEN	0.082	0.596	0.37	0.28	197.5
6	18061907	479.6	0.22	0.64	-29.6	244	303	0.032	S1	*715.5*	*362.0*	*34.8*	397.9	1703.9	82	3.5	PEN	0.066	0.802	0.56	0.38	132.3
									S2	*935.4*	*366.3*	*31.8*	395.8	1676.4	82	3.5	PEN	0.067	0.794	0.56	0.39	182.7
									S3	*746.3*	*359.4*	*33.7*	394.6	1660.9	82	3.5	PEN	0.067	0.789	0.56	0.39	149.5
7	18102210	468.3	0.16	0.77	-5.9	154	266	0.027	S1	*599.3*	*351.6*	*27.2*	363.2	957.5	85	2.2	PEN	0.150	0.904	0.55	0.42	171.9
									S2	*449.5*	*347.5*	*25.5*	357.4	957.5	85	2.2	PEN	0.151	0.882	0.55	0.42	138.0
									S3	*459.0*	*345.4*	*27.2*	359.1	957.5	85	2.2	PEN	0.151	0.888	0.548	0.42	143.4
8	20100910	464.8	0.23	0.74	-25.7	258	365	0.027	S1	*913.8*	*349.0*	*28.3*	435.0	1470.9	82	3.7	PEN	0.071	0.572	0.61	0.46	146.8
									S2	*1068.4*	*368.0*	*33.7*	456.6	1737.6	82	3.7	PEN	0.070	0.669	0.61	0.45	154.1
									S3	*930.1*	*357.5*	*29.5*	442.8	1568.0	82	3.7	PEN	0.071	0.610	0.61	0.46	149.0
9	18012711	459.7	0.10	0.54	-4.3	77	260	0.02	S1	*791.3*	*346.6*	*31.5*	438.6	867.8	75	1.4	PEN	0.172	1.000	0.37	0.23	262.4
									S2	*694.5*	*361.9*	*33.9*	465.9	867.8	75	1.4	PEN	0.171	1.000	0.37	0.19	182.3
									S3	*0.0*	--	--	<---	Source is not emitting this hour								
10	20031613	451.9	0.12	0.68	-4.3	117	360	0.025	S1	*544.1*	*357.1*	*31.5*	434.8	1051.4	80	1.5	PEN	0.215	0.603	0.46	0.40	156.4
									S2	*625.8*	*367.8*	*33.2*	442.9	1051.4	80	1.5	PEN	0.215	0.641	0.46	0.39	174.9
									S3	*364.2*	*355.7*	*28.2*	428.9	1051.4	80	1.5	PEN	0.216	0.574	0.46	0.40	105.6

For the hour ending 11 on June 3, 2019, AERMOD reported a penetrated plume at final heights for the three Martin Lake units averaging about 587 m, while the convective mixing height was 485 m (representing the value at the midpoint of the hour). For the following hour, the convective mixing height rose to about 658 m and as a result, the mixing height at the end of hour 11 was still below the three Martin Lake units' plume centerlines at about 572 m. AERMOD assigned large sigma-z values of about 228 – 242 m, resulting in a layer for effective parameters reaching well into the convective mixed layer, down to a level of about 107 m above the ground. **Figure 8** shows a plot of the sigma-w profile and the effective turbulence calculations in AERMOD. The sigma-w (green line) is the AERMOD internally calculated sigma-w extracted from the METEOR debug file.

The local value of sigma-w at the penetrated plume centerline shown in **Figure 8, *AERMOD-Simulated Sigma-w as a Function of Height for June 3, 2019, Hour Ending 11,*** is about 0.30 m/s. However, the internal AERMOD calculations of the effective sigma-w value created an average sigma-w value of more than twice the centerline value (about 0.63 m/s) in a layer between the plume centerline at ~590 m down to ~105 m. This mixing was applied to the entire mass of the penetrated plume, even though most of it remained above the mixing height even at the end of the hour. The result was an AERMOD prediction at the monitoring site of 244.0 $\mu g/m^3$, almost twice the observed value of 123.3 $\mu g/m^3$.

For the hour ending 11 on June 29, 2019, AERMOD reported a penetrated plume at final heights for the three Martin Lake units averaging about 390 m, while the convective mixing height was 296 m (representing the value at the midpoint of the hour). For the following hour, the convective mixing height rose only 10 m to 306 m (well under the plume centerline); hence the mixing height at the end of hour 11 was still below the three units' plume centerlines at about 301 m. AERMOD assigned large sigma-z values of about 125 m, resulting in a layer for effective parameters reaching well into the convective mixed layer, down to a level of about 120 m above the ground. **Figure 9, *AERMOD-Simulated Sigma-w as a Function of Height for June 29, 2019, Hour Ending 11,*** shows a plot of the sigma-w profile and the effective turbulence calculations in AERMOD.

Figure 8: AERMOD-Simulated Sigma-w as a Function of Height for June 3, 2019, Hour Ending 11

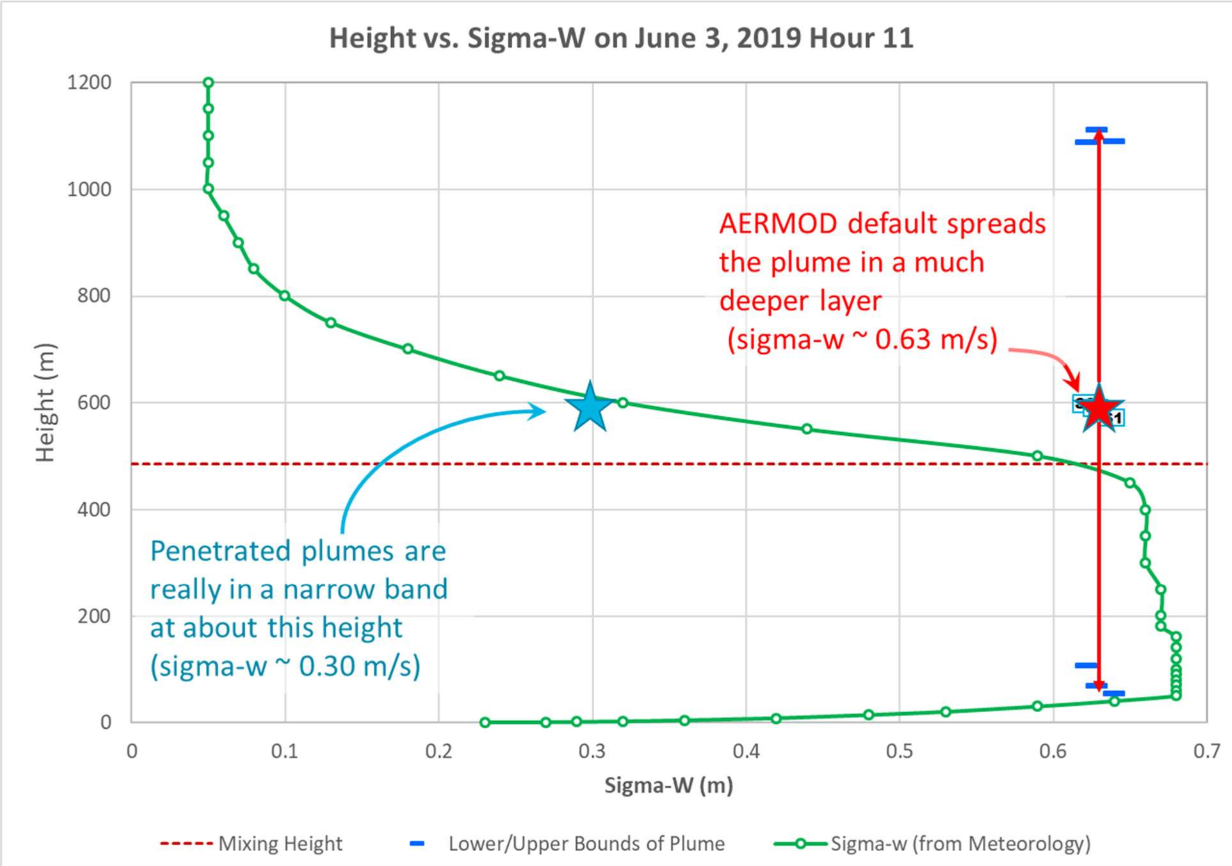
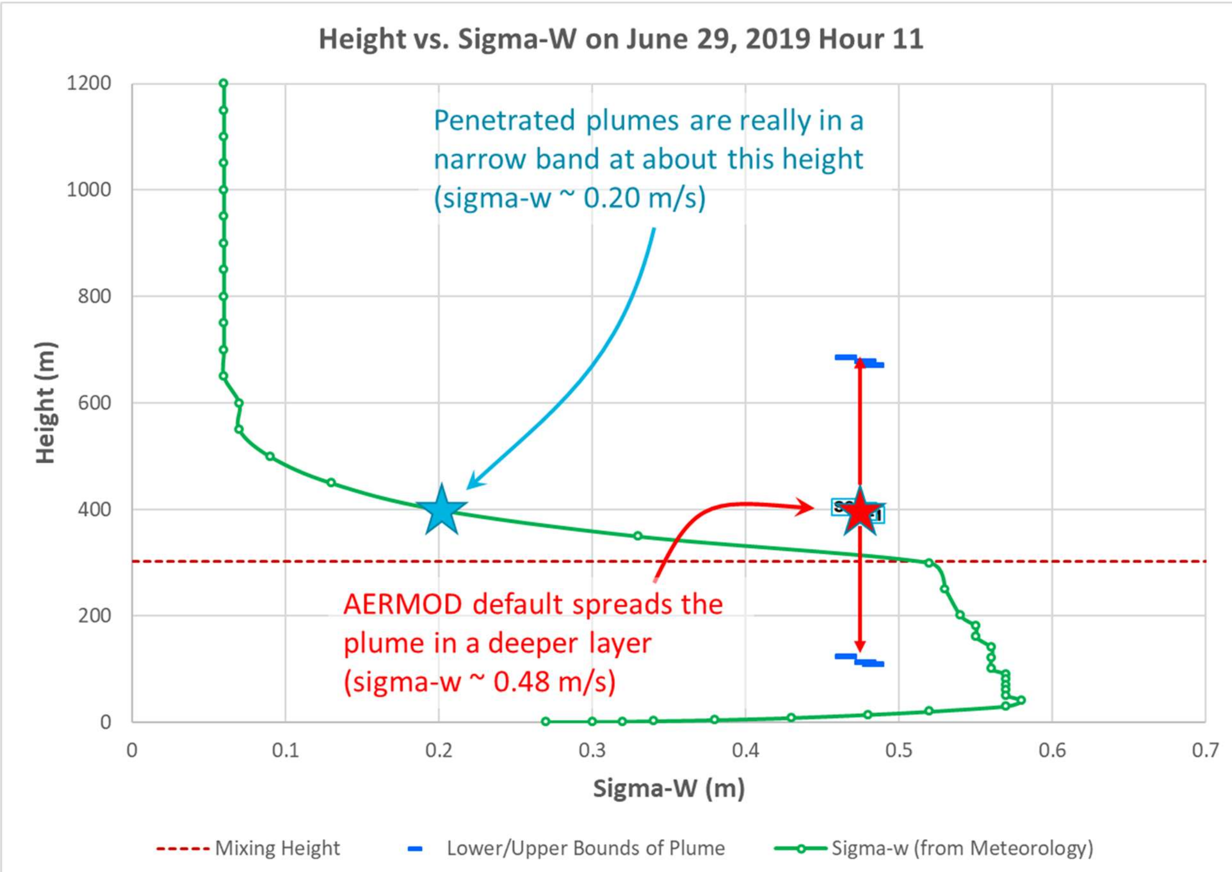


Figure 9: AERMOD-Simulated Sigma-w as a Function of Height for June 29, 2019, Hour Ending 11



The plot in **Figure 9** shows that the local value of sigma-w at the penetrated plume centerline is about 0.20 m/s. However, the internal AERMOD calculations of the effective sigma-w value created an average sigma-w value of 2.4 times the centerline value (about 0.48 m/s) in a layer between the plume centerline at ~395 m down to ~115 m. This mixing was applied to the entire mass of the penetrated plume, although most (if not all) of it remained above the mixing height at the end of the hour. The result was an AERMOD prediction at the monitoring site of 485.8 µg/m^3, well above any single hour's measurement at the monitor over the 3-year period.

The key issue is the deep vertical layer over which the effective vertical mixing parameters, especially sigma-w, are calculated. The overly deep vertical layer extends the averaging well into the convective mixed layer, resulting in an exaggerated large plume depth and an associated high impact at the ground. This feature of the penetrated plume treatment was not anticipated by the AERMIC committee in designing the model.

Other Field Databases with Penetrated Plume Overprediction Issues

To demonstrate AERMOD's overprediction tendency associated with penetrated plume events, two independent SO_2 modeling databases have been selected. The first is the 1982 – 83 Baldwin[8] database from EPA's collection of AERMOD model evaluation databases. The second is a more recent 2017 – 2019 database focusing upon the Labadie Energy Center (Labadie), owned and operated by Ameren Corporation. Both field databases focus upon coal-fueled power plants in rural areas, with Baldwin in flat terrain and Labadie surrounding by mostly flat terrain. In both datasets, the dominant SO_2 sources are tall stacks. These datasets are good candidates to evaluate since they are typical of many power-generating stations across the U.S. and are similar in many respects to the Martin Lake Power Plant (Midwest, tall stacks, flat terrain, rural).

Baldwin Power Plant

The Baldwin Power Plant database is a rural flat terrain site in southwestern Illinois with ten ambient SO_2 monitors during the 1982 – 1983 period ranging in distance from 2 to 10 km from the facility, as shown in **Figure 10, *Baldwin SO2 Monitoring Network***. The plant has three 184-meter stacks aligned approximately north-south and spaced approximately 100 meters apart, as shown in **Figure 11, *Google Earth View of the Baldwin Power Plant***.

Meteorological measurements were taken from an on-site 100-meter tower with measurements over a 1-year period from April 1, 1982 through March 31, 1983 as part of a model evaluation study. Hourly wind speed, wind direction, and temperature measurements were collected at 10 meters along with wind speed and direction at 100 meters. Upper air sounding data from Salem, Illinois, was used.

[8] EPA, AERMOD Model Evaluation Databases. Available at: https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models.

Figure 10: Baldwin SO_2 Monitoring Network

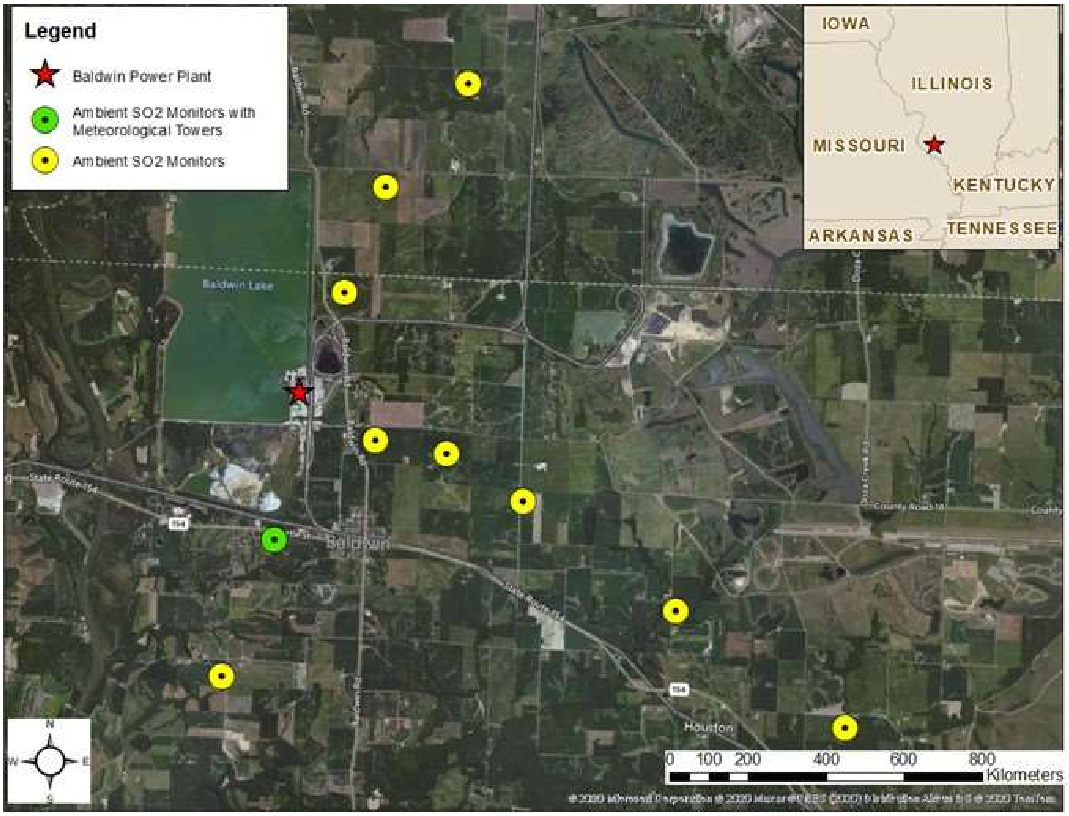


Figure 11: Google Earth View of the Baldwin Power Plant

Labadie Energy Center

Labadie is a 2,400-megawatt coal-fueled power plant located in Labadie, Missouri, approximately 55 kilometers west-southwest of St. Louis, Missouri. The station operates four boilers exhausting through three 213-meter tall stacks. Units 3 and 4 emit from a dual-flue stack and are modeled as a single, merged stack with EPA's concurrence of this approach.[9] Hourly values of SO_2 emissions, stack temperatures, and stack exit velocities used in the modeling were provided by Ameren from the Continuous Emission Monitoring System (CEMS) data.

Table 2*, Labadie Stack Locations and Typical Full Load Exhaust Parameters*, lists the stack location, height and typical exhaust parameters for each source to be included in the modeling analysis. The area surrounding Labadie is rural with mostly simple terrain, as shown in **Figure 12, *Labadie SO_2 and Meteorological Monitoring Network***. **Figure 13, *Google Earth View of the Labadie Energy Center*** shows a close-up of the three primary SO_2-source tall stacks.

The 2016 Missouri Department of Natural Resources (DNR) monitoring plan led to the establishment of two monitoring sites for SO_2 located at the Valley and Northwest locations as well as one meteorological site equipped with meteorological measurements at 2 and 10 meters located at the Valley location. **Figure 13** provides a map indicating the locations of these sites. In addition to the meteorological tower, Ameren installed a doppler SODAR/RASS in October 2015 with a height sampling range set from 40 meters to 300 meters in 20-meter increments. In addition to the Missouri monitoring plan documents cited in Section 1 that have been approved by EPA, additional documentation for the Labadie monitoring program operation is available in Quality Assurance Project Plan (QAPP) documents[10] for that project. In early 2017, Ameren installed a second 10-meter tower at the Northwest monitoring site. Since the meteorological tower at the Northwest site was installed after the beginning of the period to be considered in this evaluation study, the Valley meteorological tower dataset is used for on-site meteorology.

Table 2: Labadie Stack Locations and Typical Full Load Exhaust Parameters

Source	Easting (UTM83)[2]	Northing (UTM83)[2]	Stack Height (m)	Exit Velocity (m/s)	Temperature (K)	Diameter (m)
Unit 1	688352.17	4270445.59	213.36	34.7	443.1	6.25
Unit 2	688387.01	4270400.40	213.36	35.6	442.5	6.25
Units 3 & 4	688435.47	4270332.33	213.36	34.5	433.2	8.84[(1)]

(1) Equivalent diameter for merged flues
(2) UTM coordinates for Zone 15.

Penetrated Plume Model Evaluations on Baldwin and Labadie Databases

The Baldwin and Labadie databases were modeled using AERMOD with default options and compared against observed concentrations from nearby monitors. The 99th percentile daily maximum modeled SO_2

[9] EPA (2016). Final Technical Support Document: Missouri Area Designations for the 2010 SO_2 Primary National Ambient Air Quality Standard. Available at: https://www.epa.gov/sites/production/files/2016-07/documents/r7_mo_final_designation_tsd_07012016.pdf.

[10] Montrose, 2018. Labadie Sulfur Reduction Project Quality Assurance Project Plan.

concentrations were found to be 20%-50% higher than the observations for the Baldwin dataset. The 3-year averaged 99th percentile daily maximum modeled SO_2 concentrations were 32%-60% higher than the observed concentrations for Labadie. Other statistical measures, such as the robust highest concentration (RHC) and robust 4th highest concentration (R4HC) were about 1.5 for Baldwin and between 1.2 and 1.3 for Labadie (with 1.0 being a "perfect" and unbiased model). Therefore, indicating a 20%-50% overprediction tendency by the model.

DISTANCE-DEBUG model output from both databases indicated the dominant plume type for the top ten highest hourly SO_2 modeled concentrations were attributed to the penetrated plume, at each monitoring site. Additional details on the model evaluations for Baldwin and Labadie are provided in **Appendix A, *Model Evaluation Results for Baldwin and Labadie***. **Appendix B, *Baldwin Table and Plots,*** provides DISTANCE-DEBUG data and analysis plots for Baldwin; likewise, **Appendix C, *Labadie Tables and Plots,*** provides similar data and plots for Labadie.

Figure 12: Labadie SO_2 and Meteorological Monitoring Network

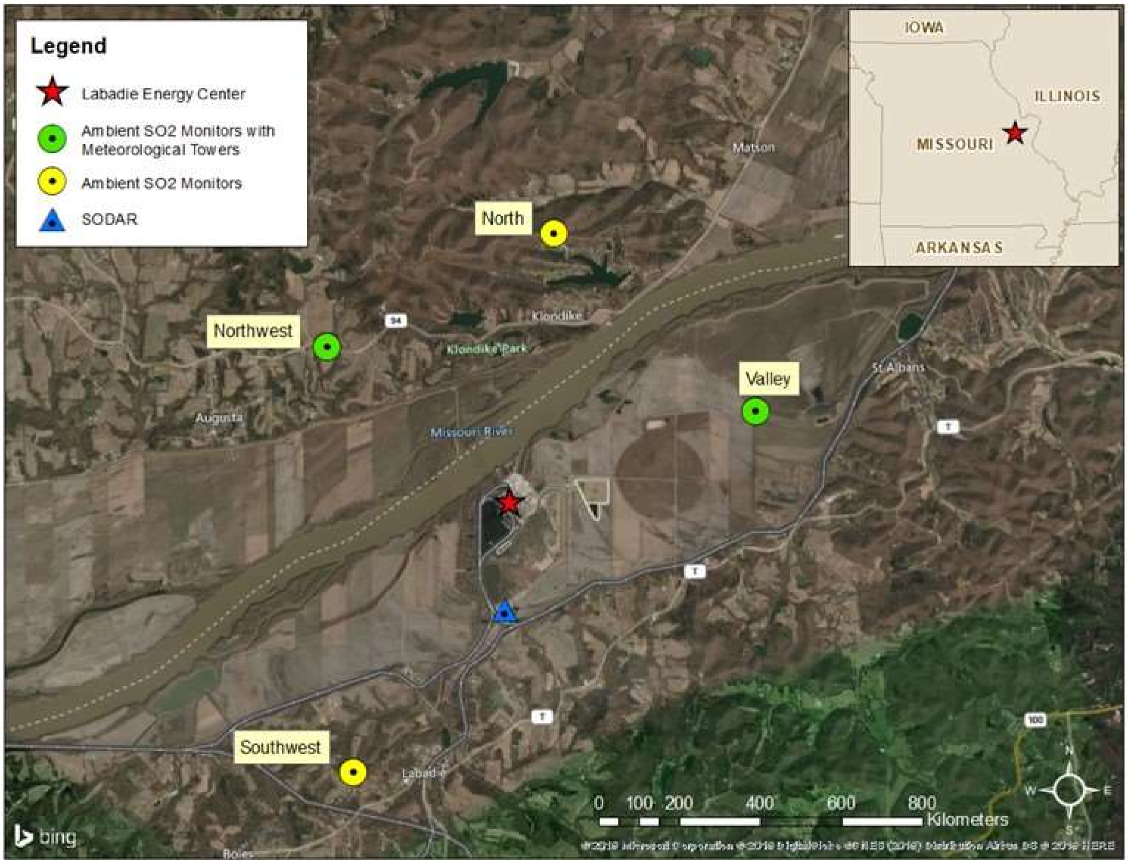


Figure 13: Google Earth View of the Labadie Energy Center

Findings by Other Investigators and Notifications to EPA

The issue of the penetrated plume behavior in AERMOD was first reported by Dr. Ken Rayner of the Western Australia Department of Environment Conservation to Mr. Robert Paine (AECOM), a member of the AERMIC committee that developed AERMOD, in the 2007-2013 period. Dr. Rayner introduced his own debugging code and found[11] that the penetrated plume was the primary component of a 50% overprediction tendency for the Collie Airshed SO_2 impacts at a key monitor ("Shotts"). This information was forwarded to Roger Brode in EPA's Office of Air Quality Planning and Standards (OAQPS) on June 11, 2014. Mr. Paine followed with a presentation[12] about the penetrated plume issue at the 11th EPA Modeling Conference, based upon the Western Australia experience and routine use of the DISTANCE-DEBUG tool to determine the cause of peak prediction issues with AERMOD.

The penetrated plume issue was included in a list of AERMOD areas of scientific formulation research in the AERMOD "white papers" discussion[13] in 2017. This issue was discussed at the 2019 Air & Waste Management Association's Specialty Modeling Conference[14] in March 2019, at the annual A&WMA conference in June 2019,[15] and also in presentations given at the 12th EPA Modeling Conference[16,17] in October 2019. The second of these presentations at the 12th EPA Modeling Conference involved new findings with an SO_2 monitoring network near the Ameren Labadie Energy Center in eastern Missouri, as reported by Ken Anderson. Dr. Weil has been working in collaboration with Mr. Paine and Mr. Christopher Warren (AECOM) for an updated evaluation study at a site with 12 monitors located in Western Australia and has helped to refine the approach to better characterize the penetrated plume behavior in an alternative modeling approach described below.

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[11] Presentation seminar by Dr. Ken Rayner on February 25. 2013: "Review of models for dispersion of tall stack plumes at Collie"; provided to Robert Paine of AECOM on 2/25/2013, and later to Roger Brode of USEPA's Office of Air Quality Planning and Standards on June 11, 2014; provided as **Attachment 5**.

[12] Paine, R., 2015. "Penetrated Plume Issues"; available at https://www3.epa.gov/ttn/scram/11thmodconf/presentations/2-4_Penetrated_Plume_Issues.pdf.

[13] Available at https://www3.epa.gov/ttn/scram/models/aermod/20170919_AERMOD_Development_White_Papers.pdf.

[14] Warren, C., R. Paine, and J. Connors, 2019. Evaluation of AERMOD SO_2 Predictions for a Research-Grade Field Experiment. Paper MO10, presented at the Air & Waste Management Association specialty conference (Guideline on Air Quality Models: Planning Ahead), March 19-21, 2019. Durham, NC.; provided as **Attachment 6**.

[15] Paine, R., J. Connors, and C. Warren, 2019. Peak Observed and AERMOD-Predicted SO_2 Concentrations in Convective Conditions. Paper #593805, presented at 112th Annual Conference, Air & Waste Management Association, Quebec City, Quebec, Canada.

[16] Paine presentation available at: ftp://newftp.epa.gov/Air/aqmg/SCRAM/conferences/2019_12th_Conference_On_Air_Quality_Modeling/Presentations/2-14_12thMC-penetrated%20plume%20presentation_01oct19_paine.pdf.

[17] Anderson presentation available at: ftp://newftp.epa.gov/Air/aqmg/SCRAM/conferences/2019_12th_Conference_On_Air_Quality_Modeling/Presentations/2-15_12thMC-Ameren-epa%2012th%20modeling%20conf%202019.pdf.

Proposed Update to AERMOD to Correct Penetrated Plume Issue: HBP modification

A proposed update to AERMOD to address the penetrated plume issue (an approach initially referred to as "HIPMOD" and now referenced as "HBP" for modifications particularly important for "highly buoyant plume")[18] was prepared for testing in 2020. This revised approach, as illustrated in the flowchart shown in **Figure 14**, ***Flowchart for AERMOD-HBP Treatment,*** involves a check on the convective mixing height for the current hour as well as the next hour to determine how much of the penetrated plume has been captured by the CBL by the end of the current hour. This is the first time that AERMOD has been enhanced to look ahead to the next hour in order to improve its performance.

The amount of the penetrated plume mass that is allowed to mix to the ground in the HBP modifications depends upon the result of this calculation. There are three possible outcomes.

Case 1: No penetrated plume impact. If the average of the current and the next hour's convective mixing height (each value represents the half-hour mark,[19] so the average is roughly at the end of the current hour) is below the bottom of the penetrated plume final height, then no portion of the penetrated plume is assumed to mix into the convective boundary layer. In that case, the contribution of the penetrated plume mass at the receptor is assumed to be zero. The "bottom" of the penetrated plume is 2.15 sigma-z's below the plume centerline height, where the concentration drops to 10% of that at the plume centerline (with a Gaussian distribution assumed).

Case 2: Full penetrated plume impact. If the mixing height at the end of the current hour is above the top of the penetrated plume, then the full mass of the plume is assumed to reach the ground, and the current AERMOD formulation is used for that hour.

Case 3: Partial penetrated plume impact. For convective mixing heights (by the end of the current hour) that are in between the bottom and top of the penetrated plume, a fraction of the plume mass computed using a vertical Gaussian distribution is assumed to reach the ground using the current AERMOD formulation. For example, the captured fraction is 0.5 if the mixing height at the end of the current hour is exactly at the penetrated plume centerline. If the mixing height at the end of the hour is below (or above) the penetrated plume centerline height, then less (or more) than half of the mass of the penetrated plume will be mixed to the ground.

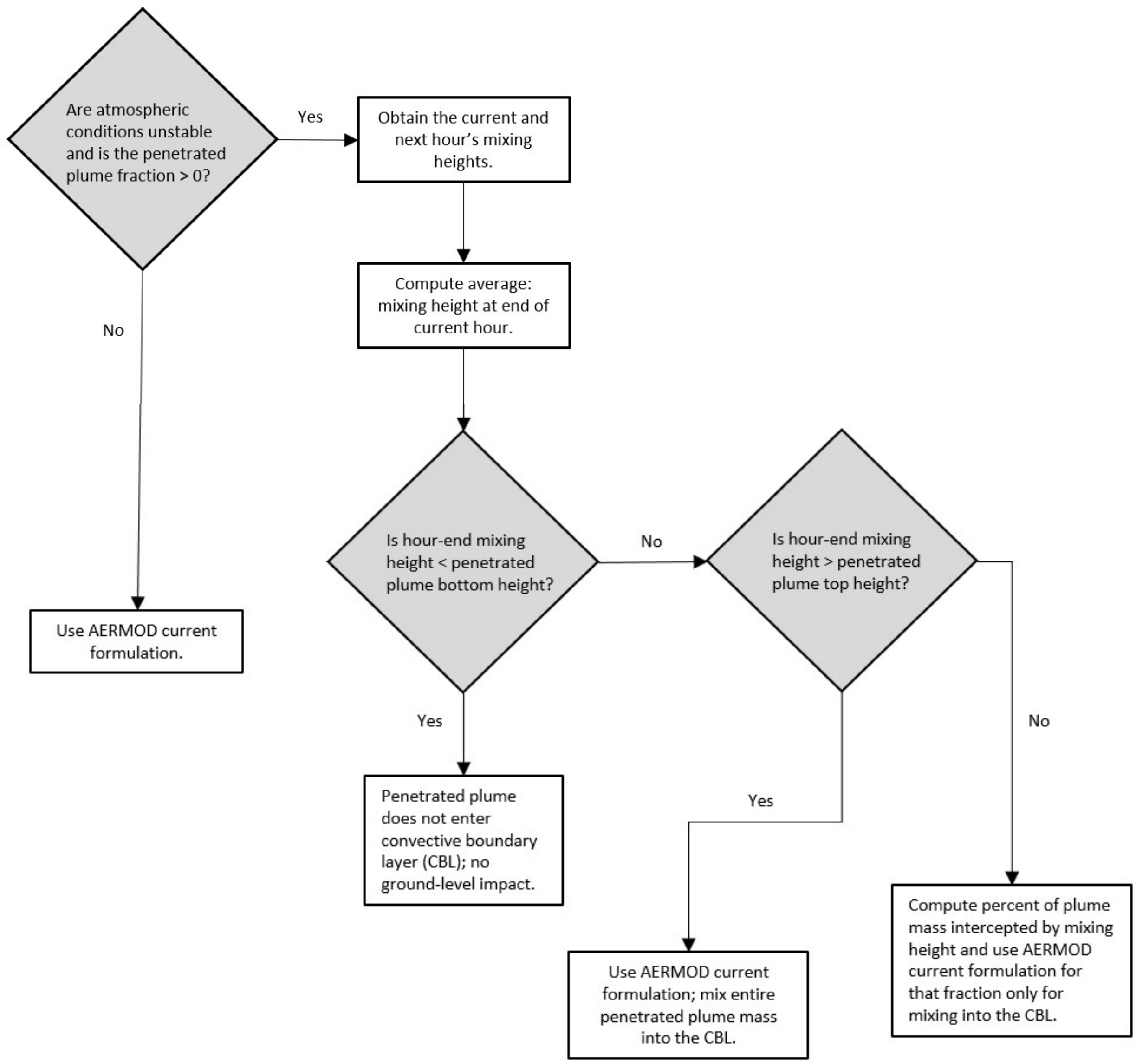
The approach implemented in the HBP modifications is quite simple, and the resulting plume behavior is consistent to what is seen in research-grade experiments such as EPRI's Bull Run study in 1982. The

[18] The name "HIPMOD" is derived from Dr. Weil's "Highly-buoyant Plume MODel" designation for this treatment, from his January 2, 2020 report to the Western Australia Department of Environmental Conservation: "New Dispersion Model for Highly-Buoyant Plumes in the Convective Boundary Layer" (included as **Attachment 3**). Although his report involves additional aspects of plume dispersion in the convective boundary layer, the HIPMOD application for AERMOD deals only with the interaction of the penetrated plume as currently coded in AERMOD version 21112 with the convective mixing layer, as described in this document.

[19] The Weil et al. (1997) paper specifically states on page 988 that "Penetrated source material is assumed to be mixed into the CBL [convective boundary layer] only when the growing, time-dependent CBL height > Zi, where Zi is the average mixed layer depth over the hour and is representative of the midpoint of the hour."

approach also extends AERMOD's capability for dealing with only one hour at a time by enabling it to determine the rate of change for the convective mixing height, with the possibility that the rising mixing height could intercept at least part of the penetrated plume in the current hour. Additionally, the HBP modifications only affect AERMOD during the critical period of the late morning through early afternoon rise of the convective mixing height into the layer containing the penetrated plume; at all other hours, AERMOD-HBP is equivalent to AERMOD run with default options.

Figure 14: Flowchart for AERMOD-HBP Treatment



Appendix A: Model Evaluation Results for Baldwin and Labadie

Model Databases Reviewed for Penetrated Plume Issues

To demonstrate AERMOD's overprediction tendency associated with penetrated plume events, two SO_2 modeling databases were selected. The first is the 1982-83 Baldwin[1] database from EPA's collection of AERMOD model evaluation databases. The second is a more recent 2017-19 database focusing upon the Labadie Energy Center (Labadie), owned and operated by Ameren Corporation. Both field databases focus upon coal-fired power plants in rural areas, with Baldwin in flat terrain and Labadie surrounding by mostly flat terrain. In both datasets, the largest SO_2 sources are tall stacks.

The Baldwin data set consisted of 1-year of on-site meteorology and ambient SO_2 measurements from 10 nearby monitors (within 2-10 km of the plant). Labadie also contains on-site meteorological data (for a 3-year period) with 4 nearby ambient monitors.

Model Setup and Evaluation Metrics

Both Baldwin and Labadie datasets were modeled using the regulatory version (19191) of AERMET/AERMOD with default options. Hourly SO_2 concentrations were extracted from the model output, via POSTFILE, and compared against the observed (measured) concentrations at each monitor location.

Quantile-Quantile (Q-Q) plots of the ranked model and observed hourly concentrations were generated for each monitor along with statistical measures of the Robust Highest Concentration (RHC) and Robust 4^{th} Highest Concentration (R4HC)[2].

To assist in identifying the dominant plume type associated with the top 10 modeled concentrations, summary tables from debug output are provided for each monitoring site. Top 10 modeled and observed concentrations are also plotted against wind speed and time of day to show any potential model biases with respect to these variables.

AERMOD Modeling Results from Baldwin

EPA's Baldwin database was modeled with default AERMOD options. Q-Q plots (ranked model and observed values paired in space) were generated for each of the 10 monitoring sites. As shown in **Figures A-1** through **A-3**, 8 of the 10 sites exhibited model overpredictions at the highest hourly SO_2 concentrations, with four at or above a factor of 2 higher benchmark. For sites 1 through 7 and 9, the top few highest ranked modeled concentrations appear to stand out from the rest of the plot, suggesting a potential anomalous event or unique condition triggering these significant differences.

With the form of the 1-hour daily maximum NAAQS being the 99^{th} percentile, the evaluation primarily focuses on this metric. The 99^{th} percentile daily maximum modeled and observed values for monitor

[1] EPA, AERMOD Model Evaluation Databases. Available at: https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

[2] The Robust Highest Concentration (RHC) is a statistical estimate of the peak concentration from a ranked concentration sample as described by Cox, W. and J. Tikvart, 1990. A statistical procedure for determining the best performing air quality simulation model, *Atmospheric Environment.* Part A. General Topics, Pages 2387-2395, ISSN 0960-1686, https://doi.org/10.1016/0960-1686(90)90331-G. The "RH4C" is a variation of the RHC in which the concentrations for the top 3 days per year are discarded (consistent with days discarded for 1-hour SO_2 form of the ambient standard), as described by Mark Garrison at the 12^{th} EPA modeling conference (ftp://newftp.epa.gov/Air/aqmg/SCRAM/conferences/2019_12th_Conference_On_Air_Quality_Modeling/Presentations/2-2-2_12thMC-Garrison_ModelPerformancePanel_12thConference_03Oct2019.pdf).

are provided in **Table A-1**. The 99th percentile daily maximum modeled concentrations are more than 20% higher than the observed at 9 of the 10 monitors, with half of the total monitors exceeding 50%.

Table A-1: Maximum Daily 99th Percentile Concentrations for Baldwin

Monitor	Model	Observed	Ratio Model/Observed
Site1	1266.6	730.0	1.74
Site2	1140.6	730.0	1.56
Site3	820.1	521.0	1.57
Site4	563.0	597.0	0.94
Site5	982.5	814.0	1.21
Site6	1281.6	851.0	1.51
Site7	1216.0	940.0	1.29
Site8	975.8	678.0	1.44
Site9	1238.9	782.0	1.58
Site10	1022.6	782.0	1.31
Values are in units of $\mu g/m^3$.			

Table A-2 summarizes the daily maximum RHC (predicted and observed) and ratio of the predicted-to-observed RHCs for each of the 10 monitoring sites. There are 9 sites that yield predicted-to-observed ratios of the RHCs of more 1.3, with 5 being greater than 1.7. Similar overprediction tendencies are seen with the R4HC (focusing on the 4th highest concentration to align with the design value of 1-hour SO_2), as shown in **Table A-3**. The geometric mean across all 10 monitoring sites further showcase the overprediction tendency of this dataset with the default options of AERMOD.

The top 25 highest 1-hour SO_2 hourly concentrations were investigated in more detail to determine under what meteorological conditions, time of day and dominant plume type these high concentrations occur at each monitor. The predicted concentrations were also compared against the observations to evaluate whether the highest modeled and observed values occur under similar conditions.

Overall, AERMOD (with default options) tends to predict the highest concentrations earlier in the day compared to the observations. Modeled top 10 hourly concentrations generally occurred early to late morning (hours ending 09 through 12), while observed high concentrations were predominantly in the late morning to early afternoon. Six of the sites yielded a majority of the top 10 highest predicted concentrations under low wind speed conditions (less than 3 m/s), while the observations were typically higher (between 3 and 6 m/s). AERMOD missed the observed high wind events (greater than 7 m/s) at sites 4, 5 and 6. Top 10 concentration plots versus hour of day and wind speed are provided in **Appendix B** (**Figures B-1** through **B-3**).

Table A-1: RHCs for Baldwin with AERMOD

	Model Scenario	RHC_{pre} (µg/m³)	RHC_{obs} (µg/m³)	RHC_{pre}/RHC_{obs}
Site1	AERMOD (Default)	1884.02	1076.26	1.75
Site2	AERMOD (Default)	1925.66	1088.62	1.77
Site3	AERMOD (Default)	1211.10	882.08	1.37
Site4	AERMOD (Default)	1074.42	1120.76	0.96
Site5	AERMOD (Default)	1722.78	1211.65	1.42
Site6	AERMOD (Default)	2241.36	1282.80	1.75
Site7	AERMOD (Default)	2100.89	1352.74	1.55
Site8	AERMOD (Default)	1682.78	985.77	1.71
Site9	AERMOD (Default)	2158.06	1250.87	1.73
Site10	AERMOD (Default)	1639.98	1245.69	1.32
			Geometric Mean	1.51

Table A-2: R4HCs for Baldwin with AERMOD

Monitor	Model Scenario	$R4HC_{pre}$ (µg/m³)	$R4HC_{obs}$ (µg/m³)	$R4HC_{pre}/RHC_{obs}$
Site1	AERMOD (Default)	1497.30	855.96	1.75
Site2	AERMOD (Default)	1364.83	807.88	1.69
Site3	AERMOD (Default)	867.89	585.35	1.48
Site4	AERMOD (Default)	737.33	730.65	1.01
Site5	AERMOD (Default)	1156.13	969.43	1.19
Site6	AERMOD (Default)	1516.55	1028.13	1.48
Site7	AERMOD (Default)	1545.80	1079.24	1.43
Site8	AERMOD (Default)	1262.85	680.58	1.86
Site9	AERMOD (Default)	1747.99	817.40	2.14
Site10	AERMOD (Default)	1245.64	906.42	1.37
		Geometric Mean		1.51

Another key aspect of this model evaluation is assessing the dominant plume type associated with the top 10 highest predicted SO_2 concentration hours. AECOM has developed debugging software that has been added to AERMOD allowing for this sort of detailed analysis to be conducted. **Table A-4** provides a summary of select meteorological parameters from the top 10 highest SO_2 predicted concentrations for Site 1. The maximum estimated mixing height (highest of mechanical and convective) is 476 meters. Except for 2 late afternoon hours (1 at Site 4 and 1 at Site 5), the top 10 highest predicted concentrations occurred with mixing heights less than 900 meters. Tables summarizing the meteorological parameters for the top 10 highest predicted concentrations are included in **Appendix B (Tables B-1** through **B-10)**.

The debug file also contains several key source and plume information for each modeled hour. **Table A-5** provides this information for Site 1 (other sites are available in **Appendix B, Tables B-11** through **B-20**). For the Baldwin database, there are 3 stacks. Plume height, distance from source, effective wind speed, plume type, meander and penetrated plume fractions, effective sigma-v and sigma-w are some of the key plume information extracted from the debugging software. The plume type helps to quickly and easily identify the dominant plume type associated with each source for a given hour. As shown in **Table A-5**, the dominant plume type associated with the top 10 highest predicted concentrations were all classified as penetrated plumes. **Tables B-11** through **B-20** in **Appendix B** indicate the penetrated plume was found to be the predominant plume type across all 10 monitoring sites for the top 10 highest hourly concentrations.

Figure A-1: Q-Q Plots for Baldwin – Sites 1 through 4

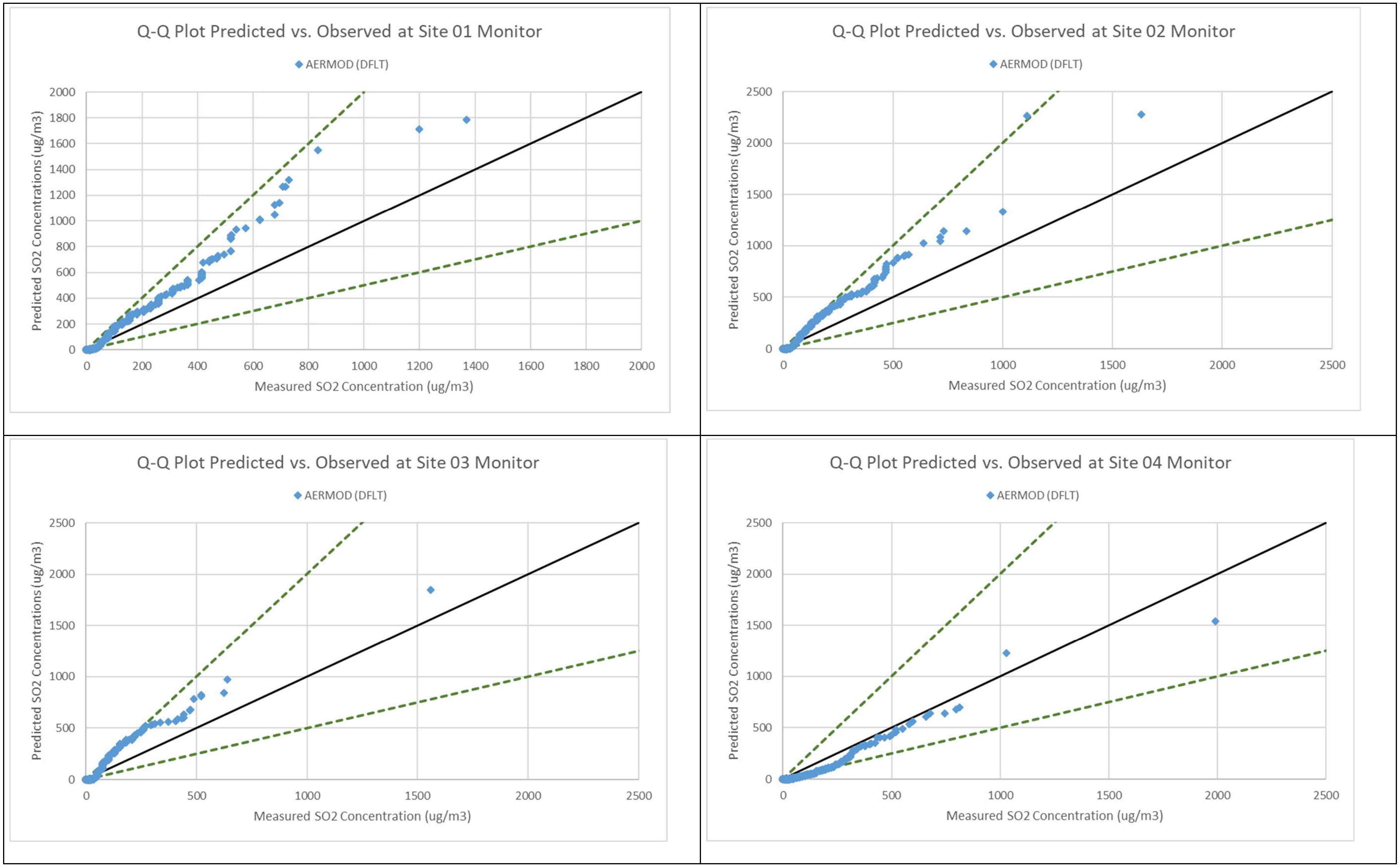


Figure A-1: Q-Q Plots for Baldwin – Sites 5 through 8

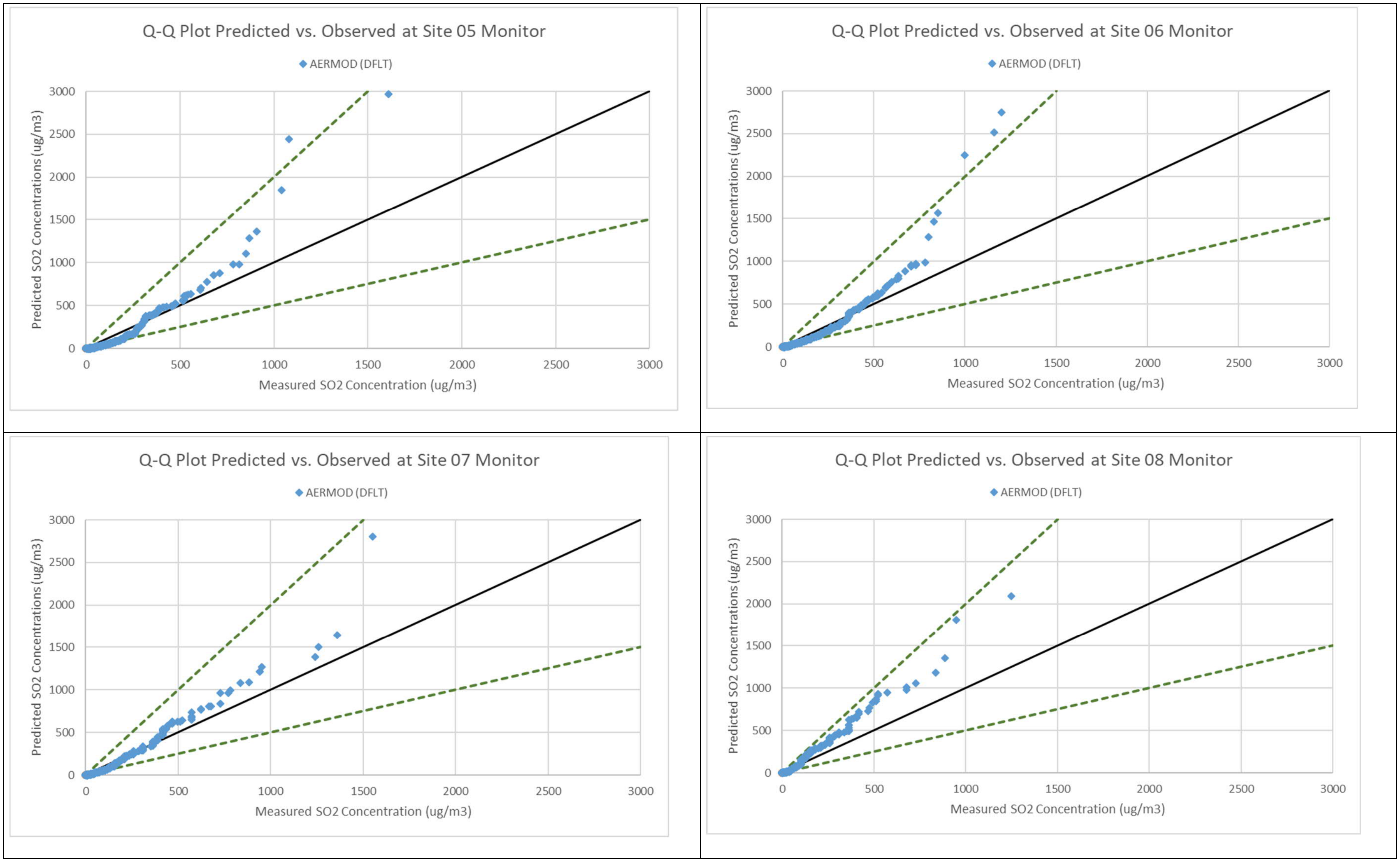


Figure A-2: Q-Q Plots for Baldwin – Sites 9 and 10

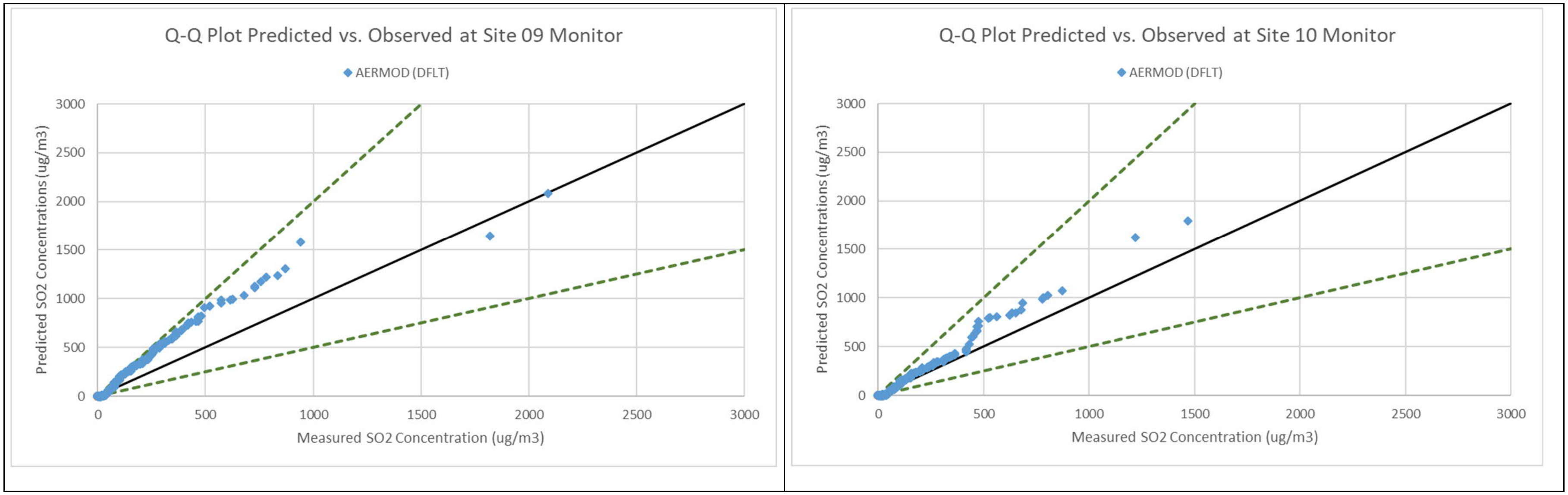


Table A-3: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 1

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83010513	0.19	0.62	-24.2	N.A.	205	315	N.A.	0.01	-9.99
2	83011313	0.17	0.61	-14.2	N.A.	165	276	N.A.	0.01	-9.99
3	83010512	0.2	0.58	-28.3	N.A.	219	263	N.A.	0.01	-9.99
4	82070318	0.21	0.67	-30.4	N.A.	238	372	N.A.	0.15	-9.99
5	82043009	0.07	0.6	-1.2	N.A.	48	262	N.A.	0.009	-9.99
6	82062811	0.25	0.83	-28.2	N.A.	303	407	N.A.	0.15	-9.99
7	83021510	0.17	0.9	-4.2	N.A.	166	255	N.A.	0.01	-9.99
8	82070317	0.27	0.75	-38.6	N.A.	333	344	N.A.	0.15	-9.99
9	82071209	0.25	1.02	-17.2	N.A.	296	476	N.A.	0.2	-9.99
10	82071710	0.33	1	-37.4	N.A.	461	403	N.A.	0.15	-9.99

AECOM Imagine it. Delivered.

Table A-4: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 1

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83010513	P	STACK1	1	418.7	1928.4	213	3.473	12502.6	5485.3	PEN	0.062	0.92	0.519	0.363	626.708	626.708	665.602	41.605	0	0	0
83010513	P	STACK2	1	416.6	1898.5	213	3.459	12451.4	5537.9	PEN	0.063	0.913	0.519	0.363	602.005	602.005	639.685	40.874	0.02	602.005	0
83010513	P	STACK3	1	414.3	1864.8	213	3.455	12439.3	5596.5	PEN	0.063	0.905	0.519	0.364	556.216	556.216	591.163	38.545	0.02	556.216	0
83011313	P	STACK1	2	412	1573.3	201	2.804	10092.7	3505.2	PEN	0.072	1	0.482	0.315	753.279	753.279	807.374	52.633	0	0	0
83011313	P	STACK2	2	399.6	1573.3	201	2.795	10060.5	3560.4	PEN	0.072	1	0.482	0.329	765.016	765.016	820.391	52.825	0.386	765.016	0
83011313	P	STACK3	2	414.8	1573.3	201	2.804	10094.6	3621.5	PEN	0.072	1	0.482	0.313	758.92	758.92	813.86	52.027	0.386	758.92	0
83010512	P	STACK1	1	387.4	1933.7	211	4.615	16614.5	5485.3	PEN	0.038	1	0.515	0.304	528.964	528.964	549.044	24.337	0	0	0
83010512	P	STACK2	1	384.7	1901.6	211	4.61	16597.1	5537.9	PEN	0.038	1	0.515	0.308	523.863	523.863	543.835	24.55	0.042	523.863	0
83010512	P	STACK3	1	382.5	1876.8	211	4.605	16578.1	5596.5	PEN	0.039	1	0.515	0.312	498.852	498.852	517.961	23.861	0.042	498.852	0
82070318	P	STACK1	1	508.9	1770.9	214	2.865	10313.2	5485.3	PEN	0.101	0.89	0.567	0.382	464.295	464.295	511.67	41.797	0	0	0
82070318	P	STACK2	1	505.9	1740.6	214	2.852	10268.6	5537.9	PEN	0.102	0.882	0.567	0.385	456.815	456.815	503.88	41.798	0.01	456.815	0
82070318	P	STACK3	1	490.6	1590.2	214	2.799	10078.1	5596.5	PEN	0.106	0.838	0.567	0.392	396.136	396.136	438.599	37.056	0.01	396.136	0
82043009	P	STACK1	1	539.7	957.2	208	1.839	6619.9	5485.3	PEN	0.118	1	0.383	0.144	389.888	389.888	438.297	27.765	0	0	0
82043009	P	STACK2	1	563.9	957.2	208	1.839	6620.9	5537.9	PEN	0.118	1	0.383	0.125	327.896	327.896	368.698	23.446	0.047	327.896	0
82043009	P	STACK3	1	471.2	957.2	208	1.835	6605.1	5596.5	PEN	0.119	1	0.383	0.22	548.835	548.835	617.849	37.797	0.047	548.835	0
82062811	P	STACK1	1	526.7	1811.2	207	3.68	13246.9	5485.3	PEN	0.089	0.777	0.684	0.491	429.667	429.667	468.371	32.839	0	0	0
82062811	P	STACK2	1	517.7	1715	207	3.655	13159.7	5537.9	PEN	0.09	0.748	0.684	0.494	409.642	409.642	447.203	31.114	0.047	409.642	0
82062811	P	STACK3	1	528.7	1832.4	207	3.675	13229.6	5596.5	PEN	0.089	0.784	0.684	0.489	426.833	426.833	465.49	32.31	0.047	426.833	0
83021510	P	STACK1	1	431.6	1514.8	209	4.554	16394.9	5485.3	PEN	0.049	1	0.606	0.366	387.318	387.318	406.14	19.731	0	0	0
83021510	P	STACK2	1	441.5	1514.8	209	4.557	16406.6	5537.9	PEN	0.049	1	0.604	0.349	388.993	388.993	407.876	19.824	0.047	388.993	0
83021510	P	STACK3	1	453.8	1514.8	209	4.56	16417.7	5596.5	PEN	0.049	1	0.603	0.329	366.375	366.375	384.138	18.715	0.047	366.375	0
82070317	P	STACK1	1	451.8	1767.5	213	4.575	16470.5	5485.3	PEN	0.059	0.862	0.672	0.45	398.481	398.481	421.753	26.68	0	0	0
82070317	P	STACK2	1	449.2	1735	213	4.551	16383.9	5537.9	PEN	0.06	0.853	0.672	0.454	390.948	390.948	414.053	26.768	0.02	390.948	0
82070317	P	STACK3	1	433.3	1540.2	213	4.379	15763.9	5596.5	PEN	0.064	0.792	0.672	0.466	337.041	337.041	358.493	23.954	0.02	337.041	0
82071209	P	STACK1	2	585.6	1559.5	209	2.614	9411.6	3505.2	PEN	0.189	0.644	0.756	0.594	408.76	408.76	490.752	56.056	0	0	0
82071209	P	STACK2	2	581.1	1559.5	209	2.613	9407.7	3560.4	PEN	0.189	0.628	0.756	0.596	390.61	390.61	469.306	53.927	0.192	390.61	0
82071209	P	STACK3	2	568.3	1537.9	209	2.61	9396.3	3621.5	PEN	0.191	0.581	0.758	0.602	341.184	341.184	410.801	47.247	0.193	341.184	0
82071710	P	STACK1	1	544.2	1753.2	205	4.796	17264.4	5485.3	PEN	0.077	0.564	0.788	0.573	337.281	337.281	363.318	25.104	0	0	0
82071710	P	STACK2	1	542.4	1730.8	205	4.788	17238.4	5537.9	PEN	0.077	0.556	0.789	0.576	341.154	341.154	367.709	25.041	0.028	341.154	0
82071710	P	STACK3	1	539.9	1698.7	205	4.777	17198.5	5596.5	PEN	0.078	0.545	0.791	0.581	333.072	333.072	359.273	24.15	0.028	333.072	0

AERMOD Modeling Results from Labadie

The Labadie modeling database was also run with default AERMOD options. Q-Q plots (ranked model and observed values paired in space) were generated for each of the 4 monitoring sites. As shown in **Figure A-4**, 3 of the 4 sites exhibited model overpredictions at the highest hourly SO_2 concentrations.

With the form of the 1-hour daily maximum NAAQS being the 99th percentile, the evaluation primarily focuses on this metric. The 99th percentile daily maximum modeled and observed values for each year and 3-year average are provided in **Table A-6**. The 3-year averaged modeled concentrations are more than 60% higher than the observed at 3 of the 4 monitors, while the North monitor is 32% higher for the model versus the observed.

Table 0-5: Maximum Daily 99th Percentile Concentrations for Labadie

Year	Valley		NW		SW		North	
	Model	Observed	Model	Observed	Model	Observed	Model	Observed
2017	110.38	54.97	77.69	54.97	103.43	57.59	106.80	78.53
2018	94.73	99.47	80.96	44.50	99.11	52.35	97.84	57.59
2019	128.50	47.12	92.48	49.73	104.22	78.53	99.88	94.23
3-year Average	111.21	67.18	83.71	49.73	102.25	62.82	101.51	76.78

Values are in units of µg/m³.

Table A-7 summarizes the daily maximum RHC (predicted and observed) and ratio of the predicted-to-observed RHCs for each of the 4 monitoring sites, using daily maximum predicted and observed concentrations. Two sites have predicted-to-observed ratios of the RHCs of more than 1.2, while a third is above 1.15. Similar overprediction tendencies are seen with the R4HC (focusing on the 4th highest concentration to align with the design value of 1-hour SO_2), as shown in **Table A-8**. The geometric mean across all 4 monitoring sites further showcase an overprediction tendency of this dataset with the default options of AERMOD.

The top 25 highest hourly SO_2 concentrations were investigated in more detail to determine under what meteorological conditions, time of day and dominant plume type these high concentrations occur at each monitor. The predicted concentrations were also compared against the observations to evaluate whether the highest modeled and observed values occur under similar conditions.

Overall, AERMOD (with default options) tends to predict the highest concentrations earlier in the day compared to the observations. Modeled top 10 hourly concentrations generally occurred early to late morning (hours ending 09 through 12), while observed high concentrations were predominantly in the late morning to early afternoon. This behavioral pattern is identical to that observed in the Baldwin database. All four of the sites had all (or almost all) of the top 10 highest predicted concentrations under low wind speed conditions (less than 3 m/s), while the observations ranged from less than 2 m/s up to 4.5 m/s. Top 10 hourly concentration plots versus hour of day and wind speed are provided in **Appendix C** (**Figure C-1**).

Table A-6: Maximum Daily RHCs for Labadie with AERMOD

Monitor	Model Scenario	RHC_{pre} (µg/m³)	RHC_{obs} (µg/m³)	RHC_{pre}/RHC_{obs}
Valley	AERMOD (Default)	198.50	147.97	1.34
NW	AERMOD (Default)	132.51	138.00	0.96
SW	AERMOD (Default)	165.42	133.68	1.24
North	AERMOD (Default)	184.21	137.91	1.34
			Geometric Mean	1.21

Table A-7: Maximum Daily R4HCs for Labadie with AERMOD

Monitor	Model Scenario	$R4HC_{pre}$ (µg/m³)	$R4HC_{obs}$ (µg/m³)	$R4HC_{pre}/RHC_{obs}$
Valley	AERMOD (Default)	169.87	118.21	1.44
NW	AERMOD (Default)	108.37	94.86	1.14
SW	AERMOD (Default)	146.20	98.51	1.48
North	AERMOD (Default)	147.99	113.89	1.30
			Geometric Mean	1.33

Table A-9 provides a summary of select meteorological parameters from the top 10 highest SO_2 predicted concentrations for the Valley monitoring site. The maximum estimated mixing height (highest of mechanical and convective) is 575 meters. At all 4 monitoring receptors, the highest mixing height value from the top 10 highest concentrations was 776 meters. Tables summarizing the meteorological parameters for the top 10 highest predicted concentrations are included in **Appendix C (Tables C-1** through **C-4)**.

Table A-10 provides modeled source and plume information for the Valley monitor (other sites are available in **Appendix C**). For the Labadie database, there are 4 stacks. Plume height, distance from source, effective wind speed, plume type, meander and penetrated plume fractions, effective sigma-v and sigma-w are some of the key plume information extracted from the debugging software. The plume type helps to quickly and easily identify the dominant plume type associated with each source for a given hour. As shown in **Table A-10**, the dominant plume type associated with the top 10 highest predicted concentrations were all classified as penetrated plumes, for the tall stack sources (Labadie1, Labadie2 and Lab34 stacks). The shorter, Labadie5, stack ended up being direct or indirect plume type, which is expected given its lower release height. **Tables C-5** through **C-8** in **Appendix C** indicate the penetrated plume was found the be the predominant plume type across all 4 Labadie monitoring sites for the top 10 highest concentrations.

Figure A-3: Q-Q Plots for Labadie – (a) Valley, (b) Northwest, (c) Southwest and (d) North Monitoring Sites

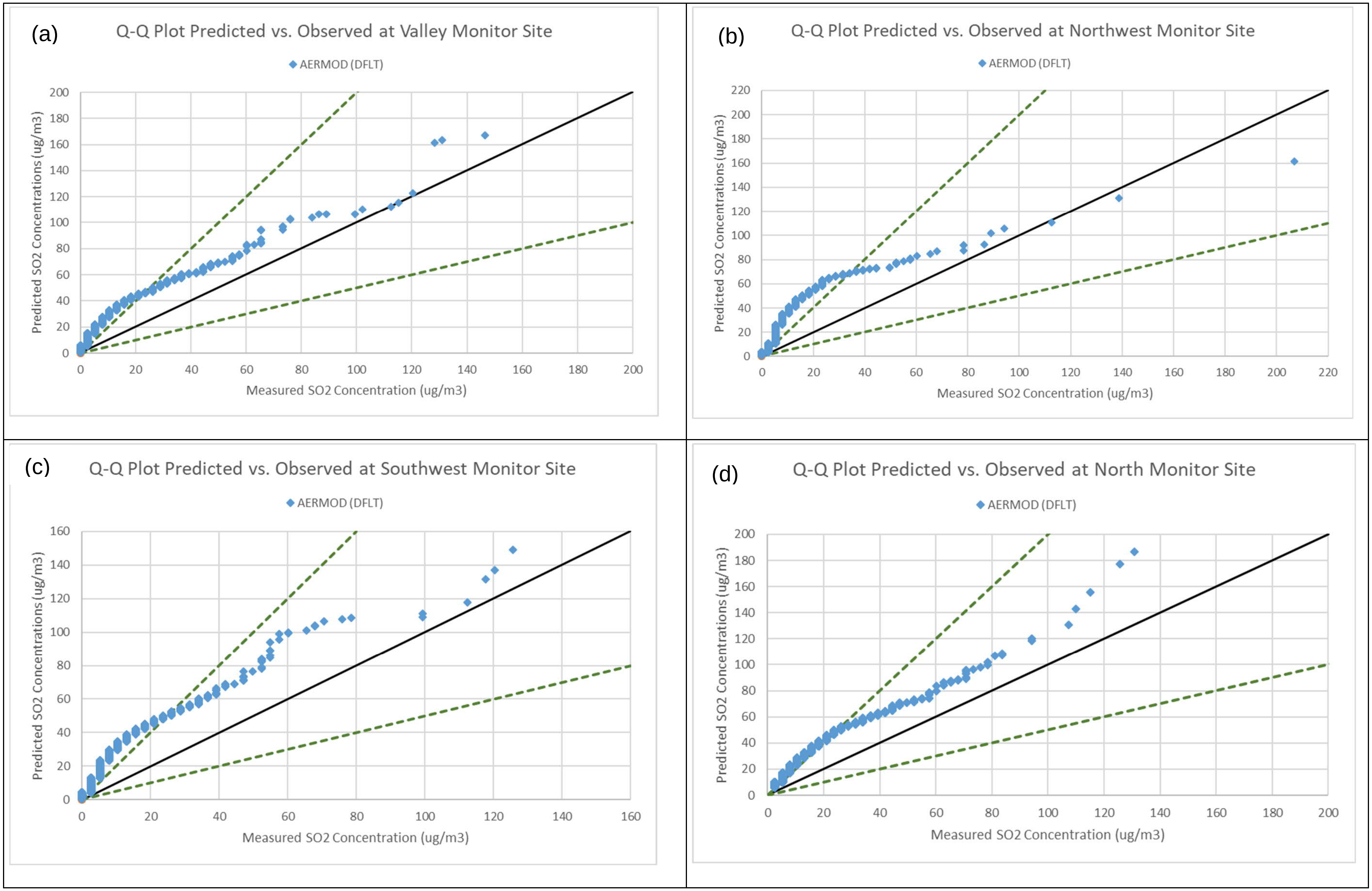


Table A-8: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Valley Monitor

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	18121013	0.22	1.06	-7.8	N.A.	244	361	N.A.	0.03	-9.99
2	17090210	0.17	1.44	-2.5	N.A.	174	575	N.A.	0.2	-9.99
3	18060610	0.22	1.17	-7.2	N.A.	252	420	N.A.	0.2	-9.99
4	17060511	0.19	1.23	-4.3	N.A.	203	450	N.A.	0.2	-9.99
5	18121016	0.16	0.52	-31	N.A.	161	434	N.A.	0.03	-9.99
6	17092910	0.25	1.26	-9.3	N.A.	301	473	N.A.	0.2	-9.99
7	17051109	0.07	0.6	-1.5	N.A.	49	310	N.A.	0.04	-9.99
8	17050910	0.33	1.1	-24.5	N.A.	460	357	N.A.	0.04	-9.99
9	17051012	0.21	1.22	-5.3	N.A.	231	417	N.A.	0.04	-9.99
10	18060609	0.17	0.95	-4.4	N.A.	171	299	N.A.	0.2	-9.99

Table A-9: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Valley Monitor

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
18121013	P	LAB34	1	475.3	1483.8	245	2.522	9079.9	3724.9	PEN	0.174	0.911	0.711	0.453	53.331	53.331	63.14	6.767	0.3	53.331	0
18121013	P	LABADIE1	1	467.9	1483.8	245	2.524	9086	3765.4	PEN	0.175	0.887	0.712	0.457	50.644	50.644	59.945	6.732	0.286	50.644	0
18121013	P	LABADIE2	1	475.5	1483.8	245	2.522	9079.7	3747.2	PEN	0.174	0.912	0.71	0.453	54.016	54.016	63.917	7.041	0.293	54.016	0
18121013	P	LABADIE5	1	18.8	52.2	241	2.488	8957.8	3723	DIR	0.185	0.001	0.727	0.499	0	0	0	0	0	0	0
17090210	P	LAB34	1	698.9	1073	245	1.489	5360.2	3724.9	PEN	0.433	0.61	0.594	0.587	80.84	80.84	126.836	20.557	0.214	80.84	0
17090210	P	LABADIE1	1	1380.1	1073	245	1.433	5157.1	3765.4	IND	0.492	0.405	0.613	0.633	36.269	36.269	61.533	10.209	0.183	36.269	0
17090210	P	LABADIE2	1	1446	1073	245	1.433	5157.1	3747.2	IND	0.483	0.441	0.613	0.633	41.596	41.596	69.69	11.484	0.197	41.596	0
17090210	P	LABADIE5	1	33.6	51.2	285	1.154	4155.6	3723	DIR	0.581	0	0.613	0.606	0	0	0	0	0	0	0
18060610	P	LAB34	1	596.3	852.4	236	1.537	5534.1	3724.9	PEN	0.457	0.946	0.704	0.493	74.976	74.976	118.695	22.934	0.004	74.976	0
18060610	P	LABADIE1	1	537.3	852.4	236	1.506	5422.7	3765.4	PEN	0.539	0.797	0.717	0.523	40.048	40.048	70.078	14.399	0.004	40.048	0
18060610	P	LABADIE2	1	541.6	852.4	236	1.508	5430.3	3747.2	PEN	0.533	0.811	0.716	0.521	41.303	41.303	71.865	14.479	0.004	41.303	0
18060610	P	LABADIE5	3	24.6	50.8	3	1.105	3977.3	4310.6	DIR	0.896	0.001	0.737	0.587	0	0	0	0	0	0	0
17060511	P	LAB34	1	746.9	1017.3	244	1.659	5973.9	3724.9	PEN	0.305	1	0.629	0.358	51.545	51.545	69.748	10.15	0.314	51.545	0
17060511	P	LABADIE1	1	645.1	1017.3	244	1.617	5819.6	3765.4	PEN	0.378	0.934	0.68	0.484	33.33	33.33	48.858	7.834	0.314	33.33	0
17060511	P	LABADIE2	1	647.8	1017.3	244	1.621	5834.3	3747.2	PEN	0.375	0.938	0.679	0.482	32.834	32.834	47.981	7.584	0.314	32.834	0
17060511	P	LABADIE5	1	28.6	50.8	244	1.493	5373.7	3723	DIR	0.482	0.002	0.722	0.549	0	0	0	0	0	0	0
18121016	P	LAB34	1	554.9	2020.9	255	1.579	5685.7	3724.9	PEN	0.18	0.784	0.457	0.205	35.476	35.476	42.22	4.708	0.458	35.476	0
18121016	P	LABADIE1	1	546.5	1921.8	255	1.585	5707.2	3765.4	PEN	0.178	0.757	0.457	0.209	36.478	36.478	43.371	4.601	0.452	36.478	0
18121016	P	LABADIE2	1	555.5	2027.6	255	1.579	5685.6	3747.2	PEN	0.18	0.786	0.457	0.205	37.164	37.164	44.27	4.795	0.455	37.164	0
18121016	P	LABADIE5	1	20.9	52.1	257	1.835	6607.5	3723	DIR	0.144	0.001	0.457	0.236	0	0	0	0	0	0	0
17092910	P	LAB34	1	688.8	1884.2	252	2.829	10183.8	3724.9	PEN	0.113	0.937	0.611	0.382	41.079	41.079	45.79	4.026	0.462	41.079	0
17092910	P	LABADIE1	1	608.3	1830.9	252	2.709	9753.1	3765.4	PEN	0.144	0.766	0.644	0.461	34.87	34.87	40.12	3.755	0.46	34.87	0
17092910	P	LABADIE2	1	604.4	1794.1	252	2.7	9720.6	3747.2	PEN	0.146	0.755	0.645	0.464	31.703	31.703	36.536	3.442	0.461	31.703	0
17092910	P	LABADIE5	2	22.3	51.2	217	2.202	7928.1	3346.3	DIR	0.192	0.001	0.669	0.504	0	0	0	0	0	0	0
17051109	P	LAB34	1	688.7	506.5	263	0.755	2719.6	3724.9	PEN	0.542	1	0.384	0.08	20.977	20.977	37.088	7.382	0.019	20.977	0
17051109	P	LABADIE1	1	606.4	506.5	263	0.755	2718.6	3765.4	PEN	0.543	1	0.384	0.149	44.909	44.909	81.805	13.858	0.018	44.909	0
17051109	P	LABADIE2	1	616.6	506.5	263	0.755	2719	3747.2	PEN	0.543	1	0.384	0.137	40.569	40.569	73.419	12.891	0.018	40.569	0
17051109	P	LABADIE5	1	46.2	51.2	263	0.615	2214.9	3723	IND	0.625	0.005	0.384	0.253	0	0	0	0	0	0	0
17050910	P	LAB34	1	534.8	1944.4	250	4.253	15309.5	3724.9	PEN	0.12	0.566	0.784	0.498	37.365	37.365	42.009	3.468	0.461	37.365	0
17050910	P	LABADIE1	1	533.2	1919.5	250	4.251	15303.4	3765.4	PEN	0.122	0.559	0.786	0.504	31.369	31.369	35.303	2.946	0.461	31.369	0
17050910	P	LABADIE2	1	523.5	1767.4	250	4.244	15280	3747.2	PEN	0.127	0.51	0.793	0.527	32.155	32.155	36.396	3.035	0.461	32.155	0
17050910	P	LABADIE5	1	15	50.9	258	3.086	11108.6	3723	DIR	0.177	0	0.887	0.733	0	0	0	0	0	0	0
17051012	P	LAB34	1	574.4	1644.6	244	4.533	16319.3	3724.9	PEN	0.08	0.911	0.771	0.624	39.664	39.664	42.79	3.631	0.354	39.664	0
17051012	P	LABADIE1	1	535.4	1644.6	244	4.134	14882.3	3765.4	PEN	0.108	0.806	0.793	0.68	30.389	30.389	33.666	3.454	0.339	30.389	0
17051012	P	LABADIE2	1	537.6	1644.6	244	4.16	14975.6	3747.2	PEN	0.107	0.813	0.792	0.676	32.549	32.549	36.012	3.504	0.344	32.549	0
17051012	P	LABADIE5	4	19.8	50.7	200	2.613	9407.9	3858.4	DIR	0.193	0.001	0.825	0.729	0	0	0	0	0	0	0
18060609	P	LAB34	3	706.4	336.4	68	0.532	1914.4	4312.9	PEN	1	1	0.6	0.098	40.85	40.85	65.308	40.85	PLUME OUT	OF WAKE	0
18060609	P	LABADIE1	2	598.5	336.4	68	0.542	1951.6	3203.1	PEN	1	1	0.612	0.207	36.971	36.971	7.96	36.971	PLUME OUT	OF WAKE	0
18060609	P	LABADIE2	2	605.7	336.4	68	0.539	1941.4	3259	PEN	1	1	0.611	0.195	36.188	36.188	6.502	36.188	PLUME OUT	OF WAKE	0
18060609	P	LABADIE5	2	31.1	50.9	39	0.689	2479.1	3346.3	DIR	1	0.002	0.652	0.488	0	0	0	0	0	0	0

Key Findings and Conclusions from Baldwin and Labadie Review

A model evaluation analysis conducted on the Baldwin and Labadie databases highlight an apparent issue with AERMOD's treatment of the penetrated plume. For early morning hours, prior to the mixing height rising and intercepting a plume located in the stable layer aloft, the plume is being mixed to the ground resulting in higher than observed ground-level concentrations. In addition to the high prediction concentrations, a peak predicted impact that is 2-3 hours earlier than the timing of higher observed concentrations is also evident in both databases.

There appears to be an apparent model bias toward early to late morning hours under low wind (less than 3 m/s) conditions when the estimated-modeled mixing height is generally less than 600-800 meters. The RHC and R4HC statistics of the top 25 concentrations also indicate an overprediction tendency with AERMOD.

AECOM's debugging software helped to identify the dominant plume type associated with the modeled-overprediction events to be the penetrated plume. This situation has been captured in other database AECOM has reviewed and as a result, has helped in the development of an approach to address this issue in AERMOD.

The purpose of these model evaluations was to highlight the issue with the treatment of the penetrated plume occurs in multiple modeling databases and not unique to just Martin Lake. Both Baldwin and Labadie provide excellent insight into this issue given the on-site data, the multiple monitors, and the hourly measurements collected.

AECOM Imagine it. Delivered.

Appendix B: Baldwin Tables and Plots

Table B-1: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 1

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83010513	0.19	0.62	-24.2	N.A.	205	315	N.A.	0.01	-9.99
2	83011313	0.17	0.61	-14.2	N.A.	165	276	N.A.	0.01	-9.99
3	83010512	0.2	0.58	-28.3	N.A.	219	263	N.A.	0.01	-9.99
4	82070318	0.21	0.67	-30.4	N.A.	238	372	N.A.	0.15	-9.99
5	82043009	0.07	0.6	-1.2	N.A.	48	262	N.A.	0.009	-9.99
6	82062811	0.25	0.83	-28.2	N.A.	303	407	N.A.	0.15	-9.99
7	83021510	0.17	0.9	-4.2	N.A.	166	255	N.A.	0.01	-9.99
8	82070317	0.27	0.75	-38.6	N.A.	333	344	N.A.	0.15	-9.99
9	82071209	0.25	1.02	-17.2	N.A.	296	476	N.A.	0.2	-9.99
10	82071710	0.33	1	-37.4	N.A.	461	403	N.A.	0.15	-9.99

Table B-2: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 2

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83011313	0.17	0.61	-14.2	N.A.	165	276	N.A.	0.01	-9.99
2	83031212	0.08	0.51	-3.8	N.A.	54	404	N.A.	0.009	-9.99
3	82062810	0.24	0.89	-19.1	N.A.	290	373	N.A.	0.2	-9.99
4	83011314	0.16	0.61	-15.1	N.A.	160	313	N.A.	0.01	-9.99
5	82071209	0.25	1.02	-17.2	N.A.	296	476	N.A.	0.2	-9.99
6	83021512	0.14	0.87	-5.7	N.A.	126	548	N.A.	0.01	-9.99
7	82053113	0.1	0.68	-4	N.A.	79	474	N.A.	0.03	-9.99
8	82062811	0.25	0.83	-28.2	N.A.	303	407	N.A.	0.15	-9.99
9	82083113	0.26	0.98	-21.2	N.A.	316	458	N.A.	0.2	-9.99
10	82061709	0.32	1	-39.4	N.A.	427	507	N.A.	0.15	-9.99

Table B-3: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 3

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83031212	0.08	0.51	-3.8	N.A.	54	404	N.A.	0.009	-9.99
2	83021413	0.13	1.46	-1.1	N.A.	116	571	N.A.	0.01	-9.99
3	82080612	0.18	0.84	-8.6	N.A.	181	366	N.A.	0.2	-9.99
4	82071209	0.25	1.02	-17.2	N.A.	296	476	N.A.	0.2	-9.99
5	82053113	0.1	0.68	-4	N.A.	79	474	N.A.	0.03	-9.99
6	83021513	0.17	1.39	-3.3	N.A.	173	685	N.A.	0.01	-9.99
7	82072609	0.2	0.89	-9.8	N.A.	209	367	N.A.	0.19	-9.99
8	83021514	0.18	1.5	-3.7	N.A.	189	821	N.A.	0.01	-9.99
9	83020416	0.11	0.98	-2.1	N.A.	87	603	N.A.	0.01	-9.99
10	83021512	0.14	0.87	-5.7	N.A.	126	548	N.A.	0.01	-9.99

Table B-4: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 4

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83020712	0.13	0.92	-2.4	N.A.	110	349	N.A.	0.003	-9.99
2	83020711	0.15	0.83	-4.7	N.A.	142	306	N.A.	0.003	-9.99
3	83020414	0.11	1.07	-1.6	N.A.	87	589	N.A.	0.003	-9.99
4	83010715	0.08	0.63	-2.3	N.A.	50	511	N.A.	0.003	-9.99
5	83020415	0.11	0.95	-2.3	N.A.	88	598	N.A.	0.003	-9.99
6	83010712	0.12	0.92	-2.5	N.A.	102	442	N.A.	0.01	-9.99
7	83020416	0.11	0.98	-2.1	N.A.	87	603	N.A.	0.01	-9.99
8	82090411	0.12	0.99	-2.8	N.A.	104	560	N.A.	0.06	-9.99
9	82072609	0.2	0.89	-9.8	N.A.	209	367	N.A.	0.19	-9.99
10	82080815	0.21	1.16	-16.8	N.A.	232	1128	N.A.	0.06	-9.99

Table B-5: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 5

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83020711	0.15	0.83	-4.7	N.A.	142	306	N.A.	0.003	-9.99
2	83020712	0.13	0.92	-2.4	N.A.	110	349	N.A.	0.003	-9.99
3	83020710	0.17	0.69	-9.3	N.A.	164	265	N.A.	0.003	-9.99
4	83010712	0.12	0.92	-2.5	N.A.	102	442	N.A.	0.01	-9.99
5	83031211	0.11	0.46	-11.6	N.A.	88	336	N.A.	0.009	-9.99
6	83020713	0.14	0.97	-3.2	N.A.	131	394	N.A.	0.003	-9.99
7	82040315	0.57	1.23	-338	N.A.	1027	1375	N.A.	0.009	-9.99
8	82082317	0.12	0.53	-10.8	N.A.	102	385	N.A.	0.06	-9.99
9	83020414	0.11	1.07	-1.6	N.A.	87	589	N.A.	0.003	-9.99
10	83020415	0.11	0.95	-2.3	N.A.	88	598	N.A.	0.003	-9.99

Table B-6: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 6

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83031211	0.11	0.46	-11.6	N.A.	88	336	N.A.	0.009	-9.99
2	83020710	0.17	0.69	-9.3	N.A.	164	265	N.A.	0.003	-9.99
3	83020711	0.15	0.83	-4.7	N.A.	142	306	N.A.	0.003	-9.99
4	83020712	0.13	0.92	-2.4	N.A.	110	349	N.A.	0.003	-9.99
5	82082317	0.12	0.53	-10.8	N.A.	102	385	N.A.	0.06	-9.99
6	82083013	0.2	0.74	-16.3	N.A.	219	321	N.A.	0.06	-9.99
7	83010715	0.08	0.63	-2.3	N.A.	50	511	N.A.	0.003	-9.99
8	83020415	0.11	0.95	-2.3	N.A.	88	598	N.A.	0.003	-9.99
9	82040516	0.61	0.39	-2661.2	N.A.	1153	279	N.A.	0.009	-9.99
10	83020414	0.11	1.07	-1.6	N.A.	87	589	N.A.	0.003	-9.99

Table B-7: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 7

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83031211	0.11	0.46	-11.6	N.A.	88	336	N.A.	0.009	-9.99
2	83020709	0.17	0.46	-31.2	N.A.	171	234	N.A.	0.003	-9.99
3	83031210	0.14	0.39	-29.4	N.A.	122	262	N.A.	0.009	-9.99
4	83020710	0.17	0.69	-9.3	N.A.	164	265	N.A.	0.003	-9.99
5	82082317	0.12	0.53	-10.8	N.A.	102	385	N.A.	0.06	-9.99
6	83010715	0.08	0.63	-2.3	N.A.	50	511	N.A.	0.003	-9.99
7	82062910	0.14	0.83	-4.3	N.A.	132	332	N.A.	0.06	-9.99
8	82122013	0.24	0.66	-37.4	N.A.	288	298	N.A.	0.015	-9.99
9	82083013	0.2	0.74	-16.3	N.A.	219	321	N.A.	0.06	-9.99
10	82083014	0.21	0.75	-18.8	N.A.	228	357	N.A.	0.06	-9.99

Table B-8: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 8

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83031211	0.11	0.46	-11.6	N.A.	88	336	N.A.	0.009	-9.99
2	83031210	0.14	0.39	-29.4	N.A.	122	262	N.A.	0.009	-9.99
3	83020709	0.17	0.46	-31.2	N.A.	171	234	N.A.	0.003	-9.99
4	83010711	0.11	0.38	-11.6	N.A.	86	192	N.A.	0.003	-9.99
5	83010715	0.08	0.63	-2.3	N.A.	50	511	N.A.	0.003	-9.99
6	83031209	0.15	0.28	-78.2	N.A.	147	188	N.A.	0.009	-9.99
7	82062910	0.14	0.83	-4.3	N.A.	132	332	N.A.	0.06	-9.99
8	83020409	0.2	0.48	-54.1	N.A.	219	286	N.A.	0.003	-9.99
9	82080512	0.14	0.47	-13.1	N.A.	129	187	N.A.	0.06	-9.99
10	82082317	0.12	0.53	-10.8	N.A.	102	385	N.A.	0.06	-9.99

Table B-9: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 9

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83010310	0.16	0.79	-5.7	N.A.	153	272	N.A.	0.01	-9.99
2	83021110	0.24	1.05	-12.2	N.A.	287	392	N.A.	0.01	-9.99
3	83010311	0.14	1.11	-2	N.A.	120	453	N.A.	0.01	-9.99
4	82062209	0.27	0.92	-21.1	N.A.	330	347	N.A.	0.19	-9.99
5	83012511	0.14	0.68	-10.4	N.A.	132	425	N.A.	0.01	-9.99
6	82112113	0.27	0.88	-27.3	N.A.	343	363	N.A.	0.05	-9.99
7	83021211	0.14	1.25	-1.4	N.A.	120	420	N.A.	0.01	-9.99
8	82043012	0.15	0.69	-10.5	N.A.	142	394	N.A.	0.03	-9.99
9	82102411	0.15	0.91	-4.7	N.A.	145	385	N.A.	0.015	-9.99
10	83021212	0.18	1.37	-2.7	N.A.	184	479	N.A.	0.01	-9.99

Table B-10: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 10

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	83010311	0.14	1.11	-2	N.A.	120	453	N.A.	0.01	-9.99
2	83021211	0.14	1.25	-1.4	N.A.	120	420	N.A.	0.01	-9.99
3	82112111	0.2	0.73	-17.8	N.A.	224	315	N.A.	0.015	-9.99
4	82060511	0.19	0.86	-9.2	N.A.	203	329	N.A.	0.06	-9.99
5	82121213	0.2	0.83	-13.4	N.A.	218	366	N.A.	0.05	-9.99
6	82102411	0.15	0.91	-4.7	N.A.	145	385	N.A.	0.015	-9.99
7	83021110	0.24	1.05	-12.2	N.A.	287	392	N.A.	0.01	-9.99
8	83021212	0.18	1.37	-2.7	N.A.	184	479	N.A.	0.01	-9.99
9	83010313	0.15	1.34	-2.5	N.A.	145	655	N.A.	0.01	-9.99
10	82112113	0.27	0.88	-27.3	N.A.	343	363	N.A.	0.05	-9.99

Table B-11: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 1

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83010513	P	STACK1	1	418.7	1928.4	213	3.473	12502.6	5485.3	PEN	0.062	0.92	0.519	0.363	626.708	626.708	665.602	41.605	0	0	0
83010513	P	STACK2	1	416.6	1898.5	213	3.459	12451.4	5537.9	PEN	0.063	0.913	0.519	0.363	602.005	602.005	639.685	40.874	0.02	602.005	0
83010513	P	STACK3	1	414.3	1864.8	213	3.455	12439.3	5596.5	PEN	0.063	0.905	0.519	0.364	556.216	556.216	591.163	38.545	0.02	556.216	0
83011313	P	STACK1	2	412	1573.3	201	2.804	10092.7	3505.2	PEN	0.072	1	0.482	0.315	753.279	753.279	807.374	52.633	0	0	0
83011313	P	STACK2	2	399.6	1573.3	201	2.795	10060.5	3560.4	PEN	0.072	1	0.482	0.329	765.016	765.016	820.391	52.825	0.386	765.016	0
83011313	P	STACK3	2	414.8	1573.3	201	2.804	10094.6	3621.5	PEN	0.072	1	0.482	0.313	758.92	758.92	813.86	52.027	0.386	758.92	0
83010512	P	STACK1	1	387.4	1933.7	211	4.615	16614.5	5485.3	PEN	0.038	1	0.515	0.304	528.964	528.964	549.044	24.337	0	0	0
83010512	P	STACK2	1	384.7	1901.6	211	4.61	16597.1	5537.9	PEN	0.038	1	0.515	0.308	523.863	523.863	543.835	24.55	0.042	523.863	0
83010512	P	STACK3	1	382.5	1876.8	211	4.605	16578.1	5596.5	PEN	0.039	1	0.515	0.312	498.852	498.852	517.961	23.861	0.042	498.852	0
82070318	P	STACK1	1	508.9	1770.9	214	2.865	10313.2	5485.3	PEN	0.101	0.89	0.567	0.382	464.295	464.295	511.67	41.797	0	0	0
82070318	P	STACK2	1	505.9	1740.6	214	2.852	10268.6	5537.9	PEN	0.102	0.882	0.567	0.385	456.815	456.815	503.88	41.798	0.01	456.815	0
82070318	P	STACK3	1	490.6	1590.2	214	2.799	10078.1	5596.5	PEN	0.106	0.838	0.567	0.392	396.136	396.136	438.599	37.056	0.01	396.136	0
82043009	P	STACK1	1	539.7	957.2	208	1.839	6619.9	5485.3	PEN	0.118	1	0.383	0.144	389.888	389.888	438.297	27.765	0	0	0
82043009	P	STACK2	1	563.9	957.2	208	1.839	6620.9	5537.9	PEN	0.118	1	0.383	0.125	327.896	327.896	368.698	23.446	0.047	327.896	0
82043009	P	STACK3	1	471.2	957.2	208	1.835	6605.1	5596.5	PEN	0.119	1	0.383	0.22	548.835	548.835	617.849	37.797	0.047	548.835	0
82062811	P	STACK1	1	526.7	1811.2	207	3.68	13246.9	5485.3	PEN	0.089	0.777	0.684	0.491	429.667	429.667	468.371	32.839	0	0	0
82062811	P	STACK2	1	517.7	1715	207	3.655	13159.7	5537.9	PEN	0.09	0.748	0.684	0.494	409.642	409.642	447.203	31.114	0.047	409.642	0
82062811	P	STACK3	1	528.7	1832.4	207	3.675	13229.6	5596.5	PEN	0.089	0.784	0.684	0.489	426.833	426.833	465.49	32.31	0.047	426.833	0
83021510	P	STACK1	1	431.6	1514.8	209	4.554	16394.9	5485.3	PEN	0.049	1	0.606	0.366	387.318	387.318	406.14	19.731	0	0	0
83021510	P	STACK2	1	441.5	1514.8	209	4.557	16406.6	5537.9	PEN	0.049	1	0.604	0.349	388.993	388.993	407.876	19.824	0.047	388.993	0
83021510	P	STACK3	1	453.8	1514.8	209	4.56	16417.7	5596.5	PEN	0.049	1	0.603	0.329	366.375	366.375	384.138	18.715	0.047	366.375	0
82070317	P	STACK1	1	451.8	1767.5	213	4.575	16470.5	5485.3	PEN	0.059	0.862	0.672	0.45	398.481	398.481	421.753	26.68	0	0	0
82070317	P	STACK2	1	449.2	1735	213	4.551	16383.9	5537.9	PEN	0.06	0.853	0.672	0.454	390.948	390.948	414.053	26.768	0.02	390.948	0
82070317	P	STACK3	1	433.3	1540.2	213	4.379	15763.9	5596.5	PEN	0.064	0.792	0.672	0.466	337.041	337.041	358.493	23.954	0.02	337.041	0
82071209	P	STACK1	2	585.6	1559.5	209	2.614	9411.6	3505.2	PEN	0.189	0.644	0.756	0.594	408.76	408.76	490.752	56.056	0	0	0
82071209	P	STACK2	2	581.1	1559.5	209	2.613	9407.7	3560.4	PEN	0.189	0.628	0.756	0.596	390.61	390.61	469.306	53.927	0.192	390.61	0
82071209	P	STACK3	2	568.3	1537.9	209	2.61	9396.3	3621.5	PEN	0.191	0.581	0.758	0.602	341.184	341.184	410.801	47.247	0.193	341.184	0
82071710	P	STACK1	1	544.2	1753.2	205	4.796	17264.4	5485.3	PEN	0.077	0.564	0.788	0.573	337.281	337.281	363.318	25.104	0	0	0
82071710	P	STACK2	1	542.4	1730.8	205	4.788	17238.4	5537.9	PEN	0.077	0.556	0.789	0.576	341.154	341.154	367.709	25.041	0.028	341.154	0
82071710	P	STACK3	1	539.9	1698.7	205	4.777	17198.5	5596.5	PEN	0.078	0.545	0.791	0.581	333.072	333.072	359.273	24.15	0.028	333.072	0

Table B-12: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 2

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83011313	P	STACK1	2	412	1573.3	201	2.804	10092.7	3505.2	PEN	0.072	1	0.482	0.315	753.279	753.279	807.374	52.633	0	0	0
83011313	P	STACK2	2	399.6	1573.3	201	2.795	10060.5	3560.4	PEN	0.072	1	0.482	0.329	765.016	765.016	820.391	52.825	0.386	765.016	0
83011313	P	STACK3	2	414.8	1573.3	201	2.804	10094.6	3621.5	PEN	0.072	1	0.482	0.313	758.92	758.92	813.86	52.027	0.386	758.92	0
83031212	P	STACK1	2	528.4	1211	190	1.147	4130.1	3505.2	PEN	0.204	0.797	0.338	0.28	760.771	760.771	919.149	142.179	0	0	0
83031212	P	STACK2	2	526.3	1211	190	1.147	4129.9	3560.4	PEN	0.204	0.791	0.338	0.28	765.554	765.554	926.428	139.215	0	0	0
83031212	P	STACK3	2	524	1211	190	1.147	4129.5	3621.5	PEN	0.205	0.783	0.338	0.281	738.598	738.598	895.203	131.032	0	0	0
82062810	P	STACK1	2	502.9	1644.9	197	3.186	11468.4	3505.2	PEN	0.102	0.869	0.699	0.504	446.376	446.376	492.045	45.81	0	0	0
82062810	P	STACK2	2	488.3	1644.9	197	3.179	11444.4	3560.4	PEN	0.106	0.825	0.699	0.513	429.92	429.92	475.574	43.558	0.372	429.92	0
82062810	P	STACK3	2	504.6	1644.9	197	3.186	11471	3621.5	PEN	0.103	0.874	0.699	0.503	458.193	458.193	505.425	45.41	0.37	458.193	0
83011314	P	STACK1	2	423.8	1736.8	191	2.696	9704.9	3505.2	PEN	0.076	0.949	0.477	0.345	372.637	372.637	397.875	63.763	0	0	0
83011314	P	STACK2	2	412.8	1714.8	191	2.694	9699	3560.4	PEN	0.076	0.912	0.477	0.35	356.097	356.097	380.738	57.52	0	0	0
83011314	P	STACK3	2	426.4	1736.8	191	2.696	9706.2	3621.5	PEN	0.076	0.957	0.477	0.343	414.503	414.503	443.336	63.759	0	0	0
82071209	P	STACK1	2	585.6	1559.5	209	2.614	9411.6	3505.2	PEN	0.189	0.644	0.756	0.594	408.76	408.76	490.752	56.056	0	0	0
82071209	P	STACK2	2	581.1	1559.5	209	2.613	9407.7	3560.4	PEN	0.189	0.628	0.756	0.596	390.61	390.61	469.306	53.927	0.192	390.61	0
82071209	P	STACK3	2	568.3	1537.9	209	2.61	9396.3	3621.5	PEN	0.191	0.581	0.758	0.602	341.184	341.184	410.801	47.247	0.193	341.184	0
83021512	P	STACK1	2	646.7	1743.6	194	2.075	7468.8	3505.2	PEN	0.175	0.528	0.579	0.502	354.73	354.73	418.927	52.457	0	0	0
83021512	P	STACK2	2	643.8	1743.6	194	2.074	7468.1	3560.4	PEN	0.176	0.518	0.579	0.503	351.25	351.25	415.177	51.008	0	0	0
83021512	P	STACK3	2	654.9	1743.6	194	2.075	7470.8	3621.5	PEN	0.175	0.555	0.579	0.499	380.324	380.324	449.657	54.469	0	0	0
82053113	P	STACK1	2	618.9	1197.7	190	1.284	4623.3	3505.2	PEN	0.269	0.75	0.446	0.37	547.954	547.954	707.623	114.351	0	0	0
82053113	STACK2	<--- Source is not emitting during this hour																			
82053113	P	STACK3	2	604.8	1197.7	190	1.283	4620.1	3621.5	PEN	0.271	0.712	0.446	0.375	497.818	497.818	645.503	100.391	0	0	0
82062811	P	STACK1	1	526.7	1811.2	207	3.68	13246.9	5485.3	PEN	0.089	0.777	0.684	0.491	429.667	429.667	468.371	32.839	0	0	0
82062811	P	STACK2	1	517.7	1715	207	3.655	13159.7	5537.9	PEN	0.09	0.748	0.684	0.494	409.642	409.642	447.203	31.114	0.047	409.642	0
82062811	P	STACK3	1	528.7	1832.4	207	3.675	13229.6	5596.5	PEN	0.089	0.784	0.684	0.489	426.833	426.833	465.49	32.31	0.047	426.833	0
82083113	P	STACK1	2	541	1698.9	197	4.218	15185.4	3505.2	PEN	0.076	0.566	0.756	0.592	291.272	291.272	313.152	26.146	0	0	0
82083113	P	STACK2	2	546.3	1764.2	197	4.222	15198.3	3560.4	PEN	0.076	0.588	0.755	0.589	309.888	309.888	333.02	27.062	0.372	309.888	0
82083113	P	STACK3	2	545.4	1753.3	197	4.221	15196.1	3621.5	PEN	0.076	0.585	0.755	0.59	314.786	314.786	338.477	26.871	0.37	314.786	0
82061709	P	STACK1	2	736.4	1655.4	201	3.692	13289.5	3505.2	IND	0.11	0.469	0.816	0.679	290.022	290.022	322.701	26.687	0	0	0
82061709	P	STACK2	2	592.7	1807.8	201	3.722	13398.3	3560.4	PEN	0.108	0.52	0.797	0.625	323.212	323.212	358.882	29.491	0.386	323.212	0
82061709	P	STACK3	2	745.7	1670.7	201	3.692	13289.5	3621.5	IND	0.111	0.474	0.816	0.679	295.202	295.202	328.685	26.866	0.386	295.202	0

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Table B-13: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 3

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83031212	P	STACK1	2	528.4	1211	190	1.147	4130.1	3505.2	PEN	0.204	0.797	0.338	0.28	760.771	760.771	919.149	142.179	0	0	0
83031212	P	STACK2	2	526.3	1211	190	1.147	4129.9	3560.4	PEN	0.204	0.791	0.338	0.28	765.554	765.554	926.428	139.215	0	0	0
83031212	P	STACK3	2	524	1211	190	1.147	4129.5	3621.5	PEN	0.205	0.783	0.338	0.281	738.598	738.598	895.203	131.032	0	0	0
83021413	P	STACK1	3	1111.3	818.8	187	1.507	5426.4	1760.1	IND	0.695	0.447	0.898	0.874	331.087	331.087	687.665	174.865	0	0	0
83021413	P	STACK2	3	1088.3	818.8	187	1.507	5426.4	1814.5	IND	0.697	0.43	0.898	0.874	319.121	319.121	670.746	166.349	0	0	0
83021413	P	STACK3	3	1099.3	818.8	187	1.507	5426.4	1875	IND	0.697	0.437	0.898	0.874	319.26	319.26	675.391	164.162	0	0	0
82080612		STACK1	<--- Source is not emitting during this hour																		
82080612	P	STACK2	3	525.2	863.1	223	1.541	5547.2	1814.5	PEN	0.3	0.955	0.602	0.443	424.615	424.615	552.489	125.843	0.056	424.615	0
82080612	P	STACK3	3	541.1	863.1	223	1.543	5553.6	1875	PEN	0.297	0.988	0.602	0.433	418.773	418.773	541.286	128.987	0.054	418.773	0
82071209	P	STACK1	2	585.6	1559.5	209	2.614	9411.6	3505.2	PEN	0.189	0.644	0.756	0.594	408.76	408.76	490.752	56.056	0	0	0
82071209	P	STACK2	2	581.1	1559.5	209	2.613	9407.7	3560.4	PEN	0.189	0.628	0.756	0.596	390.61	390.61	469.306	53.927	0.192	390.61	0
82071209	P	STACK3	2	568.3	1537.9	209	2.61	9396.3	3621.5	PEN	0.191	0.581	0.758	0.602	341.184	341.184	410.801	47.247	0.193	341.184	0
82053113	P	STACK1	2	618.9	1197.7	190	1.284	4623.3	3505.2	PEN	0.269	0.75	0.446	0.37	547.954	547.954	707.623	114.351	0	0	0
82053113		STACK2	<--- Source is not emitting during this hour																		
82053113	P	STACK3	2	604.8	1197.7	190	1.283	4620.1	3621.5	PEN	0.271	0.712	0.446	0.375	497.818	497.818	645.503	100.391	0	0	0
83021513	P	STACK1	2	1034	1751.5	202	2.603	9369.8	3505.2	IND	0.247	0.252	0.884	0.843	282.34	282.34	361.102	42.784	0	0	0
83021513	P	STACK2	2	1048.1	1754.5	202	2.603	9369.8	3560.4	IND	0.247	0.26	0.884	0.843	290.895	290.895	372.092	44.004	0.385	290.895	0
83021513	P	STACK3	2	1099.2	1754.5	202	2.603	9369.8	3621.5	IND	0.247	0.291	0.884	0.843	304.958	304.958	389.844	46.305	0.386	304.958	0
82072609	P	STACK1	10	661.9	462.6	69	0.769	2766.9	2233.8	PEN	1	1	0.637	0.37	239.172	239.172	26.309	239.172	PLUME OUT O	F WAKE	0
82072609	P	STACK2	5	684.8	462.6	69	0.778	2801.3	2465.4	PEN	1	1	0.631	0.26	231.398	231.398	0	231.398	PLUME OUT	OF WAKE	0
82072609	P	STACK3	3	636.2	462.6	69	0.777	2796.4	1875	PEN	1	1	0.634	0.314	248.094	248.094	0	248.094	PLUME OUT	OF WAKE	0
83021514	P	STACK1	3	912.7	1760.5	207	3.063	11026.3	1760.1	IND	0.196	0.129	0.956	0.914	223.822	223.822	270.565	32.488	0	0	0
83021514	P	STACK2	3	922	1774.9	207	3.063	11026.3	1814.5	IND	0.197	0.131	0.956	0.914	226.994	226.994	274.511	33.081	0.987	226.994	0
83021514	P	STACK3	2	981.5	1866.8	207	3.063	11026.3	3621.5	IND	0.212	0.145	0.956	0.914	226.001	226.001	278.246	32.123	0.357	226.001	0
83020416	P	STACK1	3	1691.3	703.7	49	0.775	2789.8	1760.1	IND	0.993	0.321	0.615	0.591	194.058	194.058	0	195.461	PLUME OUT O	F WAKE	0
83020416	P	STACK2	3	1750.5	703.7	49	0.775	2789.8	1814.5	IND	0.993	0.344	0.615	0.591	210.912	210.912	0	212.399	PLUME OUT	OF WAKE	0
83020416	P	STACK3	10	1821.5	703.7	49	0.775	2789.8	2109.7	IND	0.995	0.372	0.615	0.591	228.14	228.14	380.582	227.416	PLUME OUT	OF WAKE	0
83021512	P	STACK1	2	646.7	1743.6	194	2.075	7468.8	3505.2	PEN	0.175	0.528	0.579	0.502	354.73	354.73	418.927	52.457	0	0	0
83021512	P	STACK2	2	643.8	1743.6	194	2.074	7468.1	3560.4	PEN	0.176	0.518	0.579	0.503	351.25	351.25	415.177	51.008	0	0	0
83021512	P	STACK3	2	654.9	1743.6	194	2.075	7470.8	3621.5	PEN	0.175	0.555	0.579	0.499	380.324	380.324	449.657	54.469	0	0	0

AECOM Imagine it. Delivered.

Table B-14: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 4

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83020712	P	STACK1	5	451	928	279	1.804	6494.2	2486	PEN	0.227	0.83	0.59	0.504	788.888	788.888	977.561	144.886	0.499	788.888	0
83020712	P	STACK2	5	455.5	928	279	1.804	6493.9	2465.4	PEN	0.226	0.846	0.59	0.501	878.411	878.411	1090.514	153.323	0.5	878.411	0
83020712	P	STACK3	5	443.8	928	279	1.804	6494.8	2447.4	PEN	0.227	0.803	0.59	0.509	778.189	778.189	968.432	129.01	0.5	778.189	0
83020711	P	STACK1	5	407.8	1169.8	286	2.383	8577.9	2486	PEN	0.125	0.939	0.57	0.423	962.297	962.297	1085.643	102.228	0.926	962.297	0
83020711	P	STACK2	5	413.2	1169.8	286	2.384	8582.9	2465.4	PEN	0.126	0.957	0.57	0.413	1053.526	1053.526	1189.39	108.609	0.925 1	53.526	0
83020711	P	STACK3	5	405.4	1169.8	286	2.383	8578.4	2447.4	PEN	0.125	0.931	0.57	0.424	955.016	955.016	1077.986	95.765	0.924	955.016	0
83020414	P	STACK1	6	1217	1156.1	302	1.503	5411.1	3857.1	IND	0.397	0.19	0.664	0.642	290.501	290.501	438.156	65.949	0.287	290.501	0
83020414	P	STACK2	6	1251.6	1156.1	302	1.503	5411.1	3832.4	IND	0.397	0.204	0.664	0.642	302.133	302.133	454.717	69.897	0.289	302.133	0
83020414	P	STACK3	6	1373.6	1156.1	302	1.526	5493.3	3809.4	DIR	0.396	0.257	0.664	0.624	363.327	363.327	544.77	86.637	0.291	363.327	0
83010715	P	STACK1	7	1755.3	1459.8	311	1.318	4745.3	< 6720.9	DIR	0.232	0.492	0.397	0.371	436.339	436.339	545.347	75.198	0	436.339	0
83010715	P	STACK2	7	1709	1459.8	311	1.318	4745.2	< 6691.7	DIR	0.232	0.471	0.397	0.371	397.693	397.693	496.447	70.565	0	397.693	0
83010715	P	STACK3	7	1721.1	1459.8	311	1.318	4745.2	< 6663.1	DIR	0.232	0.476	0.397	0.371	381.976	381.976	475.974	70.177	0	381.976	0
83020415	P	STACK1	6	1395.6	1173	302	1.321	4756.5	3857.1	IND	0.401	0.217	0.601	0.576	305.145	305.145	461.401	71.514	0.287 3	5.145	0
83020415	P	STACK2	6	1416.6	1173	302	1.321	4756.5	3832.4	IND	0.401	0.225	0.601	0.576	307.797	307.797	464.564	73.325	0.289	307.797	0
83020415	P	STACK3	6	1534.4	1173	302	1.375	4951.4	3809.4	DIR	0.401	0.272	0.601	0.561	358.962	358.962	540.291	88.003	0.291	358.962	0
83010712	P	STACK1	5	532.1	1037.5	269	1.601	5762	2486	PEN	0.286	0.617	0.589	0.521	418.598	418.598	528.976	143.529	0.008	418.598	0
83010712	P	STACK2	5	531.5	1037.5	269	1.601	5761.9	2465.4	PEN	0.286	0.615	0.589	0.522	452.436	452.436	576.648	142.822	0.008	452.436	0
83010712	P	STACK3	5	535	1037.5	269	1.601	5762.6	2447.4	PEN	0.286	0.629	0.589	0.52	493.766	493.766	634.148	143.139	0.008	493.766	0
83020416	P	STACK1	3	1691.3	703.7	49	0.775	2789.8	1760.1	IND	0.993	0.321	0.615	0.591	194.058	194.058	0	195.461	PLUME OUT	OF WAKE	0
83020416	P	STACK2	3	1750.5	703.7	49	0.775	2789.8	1814.5	IND	0.993	0.344	0.615	0.591	210.912	210.912	0	212.399	PLUME OUT	OF WAKE	0
83020416	P	STACK3	10	1821.5	703.7	49	0.775	2789.8	2109.7	IND	0.995	0.372	0.615	0.591	228.14	228.14	380.582	227.416	PLUME OUT	OF WAKE	0
82090411	P	STACK1	4	689.5	1054.4	314	1.418	5104.9	1396.3	PEN	0.415	0.612	0.619	0.55	289.336	289.336	428.723	93.197	0.763	289.336	0
82090411	P	STACK2	6	697.5	1054.4	314	1.421	5114.1	3832.4	PEN	0.434	0.634	0.617	0.543	300.973	300.973	450.981	105.183	0	300.973	0
82090411		STACK3	<--- Source is not emitting during this hour																		
82072609	P	STACK1	10	661.9	462.6	69	0.769	2766.9	2233.8	PEN	1	1	0.637	0.37	239.172	239.172	26.309	239.172	PLUME	OUT OF WAKE	0
82072609	P	STACK2	5	684.8	462.6	69	0.778	2801.3	2465.4	PEN	1	1	0.631	0.26	231.398	231.398	0	231.398	PLUME	OUT OF WAKE	0
82072609	P	STACK3	3	636.2	462.6	69	0.777	2796.4	1875	PEN	1	1	0.634	0.314	248.094	248.094	0	248.094	PLUME	OUT OF WAKE	0
82080815	P	STACK1	4	410.8	811.7	292	3.051	10983.5	1396.3	DIR	0.14	0.009	0.794	0.694	223.786	223.786	255.463	28.704	1	223.786	0
82080815	P	STACK2	5	782.1	1554.7	292	3.173	11423.9	2465.4	DIR	0.135	0.041	0.794	0.714	154.494	154.494	175.807	17.599	0.924	154.494	0
82080815	P	STACK3	6	911.6	1768.2	292	3.206	11540.1	3809.4	DIR	0.139	0.056	0.794	0.718	149.58	149.58	171.177	16.226	0.497	149.58	0

Table B-15: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 5

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83020711	P	STACK1	5	407.8	1169.8	286	2.383	8577.9	2486	PEN	0.125	0.939	0.57	0.423	962.297	962.297	1085.643	102.228	0.926	962.297	0
83020711	P	STACK2	5	413.2	1169.8	286	2.384	8582.9	2465.4	PEN	0.126	0.957	0.57	0.413	1053.526	1053.526	1189.39	108.609	0.925	1053.526	0
83020711	P	STACK3	5	405.4	1169.8	286	2.383	8578.4	2447.4	PEN	0.125	0.931	0.57	0.424	955.016	955.016	1077.986	95.765	0.924	955.016	0
83020712	P	STACK1	5	451	928	279	1.804	6494.2	2486	PEN	0.227	0.83	0.59	0.504	788.888	788.888	977.561	144.886	0.499	788.888	0
83020712	P	STACK2	5	455.5	928	279	1.804	6493.9	2465.4	PEN	0.226	0.846	0.59	0.501	878.411	878.411	1090.514	153.323	0.5	878.411	0
83020712	P	STACK3	5	443.8	928	279	1.804	6494.8	2447.4	PEN	0.227	0.803	0.59	0.509	778.189	778.189	968.432	129.01	0.5	778.189	0
83020710	P	STACK1	6	397.9	1391.7	290	2.812	10122.4	3857.1	PEN	0.083	1	0.518	0.259	824.208	824.208	892.964	67.517	0.486	824.208	0
83020710	P	STACK2	6	395.2	1391.7	290	2.812	10121.9	3832.4	PEN	0.083	1	0.518	0.263	849.679	849.679	920.776	67.051	0.486	849.679	0
83020710	P	STACK3	6	393.7	1391.7	290	2.812	10121.7	3809.4	PEN	0.083	1	0.518	0.265	840.465	840.465	910.944	64.164	0.486	840.465	0
83010712	P	STACK1	5	532.1	1037.5	269	1.601	5762	2486	PEN	0.286	0.617	0.589	0.521	418.598	418.598	528.976	143.529	0.008	418.598	0
83010712	P	STACK2	5	531.5	1037.5	269	1.601	5761.9	2465.4	PEN	0.286	0.615	0.589	0.522	452.436	452.436	576.648	142.822	0.008	452.436	0
83010712	P	STACK3	5	535	1037.5	269	1.601	5762.6	2447.4	PEN	0.286	0.629	0.589	0.52	493.766	493.766	634.148	143.139	0.008	493.766	0
83031211	P	STACK1	6	456.6	1814.9	298	2.001	7204.4	3857.1	PEN	0.082	0.921	0.343	0.216	979.745	979.745	1060.581	69.248	0.489	979.745	0
83031211	P	STACK2	7	454.8	1814.9	298	2.001	7204.4	6691.7	PEN	0.099	0.916	0.343	0.216	949.105	949.105	1046.678	60.297	0.017	949.105	0
83031211	P	STACK3	7	453.4	1814.9	298	2.001	7204.4	6663.1	PEN	0.099	0.911	0.343	0.217	907.798	907.798	1001.036	57.402	0.017	907.798	0
83020713	P	STACK1	5	466.5	1322.9	275	2.412	8684.4	2486	PEN	0.148	0.613	0.629	0.553	359.451	359.451	408.135	78.124	0.154	359.451	0
83020713	P	STACK2	5	468.8	1322.9	275	2.413	8685.1	2465.4	PEN	0.147	0.625	0.629	0.552	416.195	416.195	474.096	80.989	0.153	416.195	0
83020713	P	STACK3	5	824.4	1322.9	275	2.41	8677.8	2447.4	IND	0.149	0.476	0.633	0.588	324.798	324.798	371.682	56.427	0.153	324.798	0
82040315	P	STACK1	5	322.9	1760.3	288	16.713	60168.6	2486	DIR	0.013	0.002	1.222	0.994	453.869	104.563	105.931	3.949	0.924	482.397	0
82040315	P	STACK2	5	335	1857.1	288	16.741	60269.2	2465.4	DIR	0.013	0.002	1.22	0.993	528.62	115.084	116.559	3.742	0.924	562.594	0
82040315	STACK3	<--- Source is not emitting during this hour																			
82082317	P ST	6	589.9	1263.1	298	1.384	4983.4	3857.1 PEN	0.186	1	0.387	0.204	735.041	735.041	882.4	88.496	0.489	735.041	0		
82082317	P ST	6	598.4	1263.1	298	1.385	4984.8	3832.4 PEN	0.185	1	0.387	0.196	727.478	727.478	872.341	89.013	0.489	727.478	0		
82082317	STACK3	<--- Source is not emitting during this hour																			
83020414	P	STACK1	6	1217	1156.1	302	1.503	5411.1	3857.1	IND	0.397	0.19	0.664	0.642	290.501	290.501	438.156	65.949	0.287	290.501	0
83020414	P	STACK2	6	1251.6	1156.1	302	1.503	5411.1	3832.4	IND	0.397	0.204	0.664	0.642	302.133	302.133	454.717	69.897	0.289	302.133	0
83020414	P	STACK3	6	1373.6	1156.1	302	1.526	5493.3	3809.4	DIR	0.396	0.257	0.664	0.624	363.327	363.327	544.77	86.637	0.291	363.327	0
83020415	P	STACK1	6	1395.6	1173	302	1.321	4756.5	3857.1	IND	0.401	0.217	0.601	0.576	305.145	305.145	461.401	71.514	0.287	305.145	0
83020415	P	STACK2	6	1416.6	1173	302	1.321	4756.5	3832.4	IND	0.401	0.225	0.601	0.576	307.797	307.797	464.564	73.325	0.289	307.797	0
83020415	P	STACK3	6	1534.4	1173	302	1.375	4951.4	3809.4	DIR	0.401	0.272	0.601	0.561	358.962	358.962	540.291	88.003	0.291	358.962	0

AECOM Imagine it. Delivered.

Table B-16: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 6

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83031211	P	STACK1	6	456.6	1814.9	298	2.001	7204.4	3857.1	PEN	0.082	0.921	0.343	0.216	979.745	979.745	1060.581	69.248	0.489	979.745	0
83031211	P	STACK2	7	454.8	1814.9	298	2.001	7204.4	6691.7	PEN	0.099	0.916	0.343	0.216	949.105	949.105	1046.678	60.297	0.017	949.105	0
83031211	P	STACK3	7	453.4	1814.9	298	2.001	7204.4	6663.1	PEN	0.099	0.911	0.343	0.217	907.798	907.798	1001.036	57.402	0.017	907.798	0
83020710	P	STACK1	6	397.9	1391.7	290	2.812	10122.4	3857.1	PEN	0.083	1	0.518	0.259	824.208	824.208	892.964	67.517	0.486	824.208	0
83020710	P	STACK2	6	395.2	1391.7	290	2.812	10121.9	3832.4	PEN	0.083	1	0.518	0.263	849.679	849.679	920.776	67.051	0.486	849.679	0
83020710	P	STACK3	6	393.7	1391.7	290	2.812	10121.7	3809.4	PEN	0.083	1	0.518	0.265	840.465	840.465	910.944	64.164	0.486	840.465	0
83020711	P	STACK1	5	407.8	1169.8	286	2.383	8577.9	2486	PEN	0.125	0.939	0.57	0.423	962.297	962.297	1085.643	102.228	0.926	962.297	0
83020711	P	STACK2	5	413.2	1169.8	286	2.384	8582.9	2465.4	PEN	0.126	0.957	0.57	0.413	1053.526	1053.526	1189.39	108.609	0.925	1053.526	0
83020711	P	STACK3	5	405.4	1169.8	286	2.383	8578.4	2447.4	PEN	0.125	0.931	0.57	0.424	955.016	955.016	1077.986	95.765	0.924	955.016	0
83020712	P	STACK1	5	451	928	279	1.804	6494.2	2486	PEN	0.227	0.83	0.59	0.504	788.888	788.888	977.561	144.886	0.499	788.888	0
83020712	P	STACK2	5	455.5	928	279	1.804	6493.9	2465.4	PEN	0.226	0.846	0.59	0.501	878.411	878.411	1090.514	153.323	0.5	878.411	0
83020712	P	STACK3	5	443.8	928	279	1.804	6494.8	2447.4	PEN	0.227	0.803	0.59	0.509	778.189	778.189	968.432	129.01	0.5	778.189	0
82082317	P	STACK1	6	589.9	1263.1	298	1.384	4983.4	3857.1	PEN	0.186	1	0.387	0.204	735.041	735.041	882.4	88.496	0.489	735.041	0
82082317	P	STACK2	6	598.4	1263.1	298	1.385	4984.8	3832.4	PEN	0.185	1	0.387	0.196	727.478	727.478	872.341	89.013	0.489	727.478	0
82082317		STACK3	<--- Source is not emitting during this hour																		
82083013	P	STACK1	6	505.5	1427.7	291	2.747	9890.8	3857.1	PEN	0.106	1	0.584	0.252	427.477	427.477	473.41	39.885	0.497	427.477	0
82083013	P	STACK2	6	508.8	1427.7	291	2.748	9891.4	3832.4	PEN	0.106	1	0.584	0.247	435.896	435.896	482.746	39.862	0.498	435.896	0
82083013	P	STACK3	6	515.5	1427.7	291	2.748	9892.4	3809.4	PEN	0.106	1	0.584	0.238	418.184	418.184	463.1	37.627	0.498	418.184	0
83010715	P	STACK1	7	1755.3	1459.8	311	1.318	4745.3	6720.9	DIR	0.232	0.492	0.397	0.371	436.339	436.339	545.347	75.198	0	436.339	0
83010715	P	STACK2	7	1709	1459.8	311	1.318	4745.2	6691.7	DIR	0.232	0.471	0.397	0.371	397.693	397.693	496.447	70.565	0	397.693	0
83010715	P	STACK3	7	1721.1	1459.8	311	1.318	4745.2	6663.1	DIR	0.232	0.476	0.397	0.371	381.976	381.976	475.974	70.177	0	381.976	0
83020415	P	STACK1	6	1395.6	1173	302	1.321	4756.5	3857.1	IND	0.401	0.217	0.601	0.576	305.145	305.145	461.401	71.514	0.287	305.145	0
83020415	P	STACK2	6	1416.6	1173	302	1.321	4756.5	3832.4	IND	0.401	0.225	0.601	0.576	307.797	307.797	464.564	73.325	0.289	307.797	0
83020415	P	STACK3	6	1534.4	1173	302	1.375	4951.4	3809.4	DIR	0.401	0.272	0.601	0.561	358.962	358.962	540.291	88.003	0.291	358.962	0
82040516	P	STACK1	6	315.8	1810.6	294	18.573	66863.6	3857.1	DIR	0.011	0.007	1.088	0.752	466.667	123.656	124.948	3.198	0.82	541.964	0
82040516	P	STACK2	6	327.6	1914	294	18.605	66979.5	3832.4	DIR	0.011	0.008	1.086	0.75	500.227	122.456	123.724	3.112	0.821	582.669	0
82040516		STACK3	<--- Source is not emitting during this hour																		
83020414	P	STACK1	6	1217	1156.1	302	1.503	5411.1	3857.1	IND	0.397	0.19	0.664	0.642	290.501	290.501	438.156	65.949	0.287	290.501	0
83020414	P	STACK2	6	1251.6	1156.1	302	1.503	5411.1	3832.4	IND	0.397	0.204	0.664	0.642	302.133	302.133	454.717	69.897	0.289	302.133	0
83020414	P	STACK3	6	1373.6	1156.1	302	1.526	5493.3	3809.4	DIR	0.396	0.257	0.664	0.624	363.327	363.327	544.77	86.637	0.291	363.327	0

Table B-17: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 7

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRM VAL	POT. TEMP. GRAD.
83031211	P	STACK1	6	456.6	1814.9	298	2.001	7204.4	3857.1	PEN	0.082	0.921	0.343	0.216	979.745	979.745	1060.581	69.248	0.489	979.745	0
83031211	P	STACK2	7	454.8	1814.9	298	2.001	7204.4	6691.7	PEN	0.099	0.916	0.343	0.216	949.105	949.105	1046.678	60.297	0.017	949.105	0
83031211	P	STACK3	7	453.4	1814.9	298	2.001	7204.4	6663.1	PEN	0.099	0.911	0.343	0.217	907.798	907.798	1001.036	57.402	0.017	907.798	0
83020709	P	STACK1	7	387.3	1964.3	296	3.74	13462.5	6720.9	PEN	0.046	1	0.424	0.136	535.807	535.807	560.451	27.271	0.015	535.807	0
83020709	P	STACK2	7	383.3	1917.9	296	3.74	13462.5	6691.7	PEN	0.046	1	0.424	0.139	553.672	553.672	579.163	27.039	0.015	553.672	0
83020709	P	STACK3	7	383.5	1919.5	296	3.74	13462.5	6663.1	PEN	0.046	1	0.424	0.138	552.422	552.422	577.852	25.947	0.015	552.422	0
83031210	P	STACK1	8	424.5	1940.7	304	2.792	10050.8	9877.5	PEN	0.072	1	0.346	0.121	626.397	626.397	672.724	32.034	0	626.397	0
83031210	P	STACK2	8	422.4	1920.3	304	2.792	10050.7	9846.7	PEN	0.072	1	0.346	0.122	606.112	606.112	650.873	31.81	0	606.112	0
83031210	P	STACK3	8	426.5	1960.1	304	2.792	10050.9	9816.2	PEN	0.072	1	0.346	0.119	575.179	575.179	617.304	31.118	0	575.179	0
83020710	P	STACK1	6	397.9	1391.7	290	2.812	10122.4	3857.1	PEN	0.083	1	0.518	0.259	824.208	824.208	892.964	67.517	0.486	824.208	0
83020710	P	STACK2	6	395.2	1391.7	290	2.812	10121.9	3832.4	PEN	0.083	1	0.518	0.263	849.679	849.679	920.776	67.051	0.486	849.679	0
83020710	P	STACK3	6	393.7	1391.7	290	2.812	10121.7	3809.4	PEN	0.083	1	0.518	0.265	840.465	840.465	910.944	64.164	0.486	840.465	0
82082317	P	STACK1	6	589.9	1263.1	298	1.384	4983.4	3857.1	PEN	0.186	1	0.387	0.204	735.041	735.041	882.4	88.496	0.489	735.041	0
82082317	P	STACK2	6	598.4	1263.1	298	1.385	4984.8	3832.4	PEN	0.185	1	0.387	0.196	727.478	727.478	872.341	89.013	0.489	727.478	0
82082317		STACK3	<--- Source is not emitting during this hour																		
83010715	P	STACK1	7	1755.3	1459.8	311	1.318	4745.3	6720.9	DIR	0.232	0.492	0.397	0.371	436.339	436.339	545.347	75.198	0	436.339	0
83010715	P	STACK2	7	1709	1459.8	311	1.318	4745.2	6691.7	DIR	0.232	0.471	0.397	0.371	397.693	397.693	496.447	70.565	0	397.693	0
83010715	P	STACK3	7	1721.1	1459.8	311	1.318	4745.2	6663.1	DIR	0.232	0.476	0.397	0.371	381.976	381.976	475.974	70.177	0	381.976	0
82062910	P	STACK1	7	521.6	1246	306	2.594	9336.7	6720.9	PEN	0.13	1	0.565	0.29	428.109	428.109	485.475	44.219	0.003	428.109	0
82062910	P	STACK2	7	518.5	1246	306	2.593	9336.3	6691.7	PEN	0.131	1	0.565	0.294	417.064	417.064	473.269	44.331	0.003	417.064	0
82062910	P	STACK3	7	500.2	1246	306	2.592	9332.3	6663.1	PEN	0.135	1	0.565	0.321	369.657	369.657	420.854	40.754	0.003	369.657	0
82122013	P	STACK1	7	432.6	1868.1	296	4.837	17412.3	6720.9	PEN	0.048	1	0.606	0.277	356.654	356.654	373.649	20.18	0.015	356.654	0
82122013	P	STACK2	7	425.7	1803.9	296	4.836	17409.7	6691.7	PEN	0.048	1	0.606	0.286	360.171	360.171	377.433	19.805	0.015	360.171	0
82122013	P	STACK3	7	434.4	1884.2	296	4.837	17413.7	6663.1	PEN	0.048	1	0.606	0.274	369.987	369.987	387.591	19.72	0.015	369.987	0
82083013	P	STACK1	6	505.5	1427.7	291	2.747	9890.8	3857.1	PEN	0.106	1	0.584	0.252	427.477	427.477	473.41	39.885	0.497	427.477	0
82083013	P	STACK2	6	508.8	1427.7	291	2.748	9891.4	3832.4	PEN	0.106	1	0.584	0.247	435.896	435.896	482.746	39.862	0.498	435.896	0
82083013	P	STACK3	6	515.5	1427.7	291	2.748	9892.4	3809.4	PEN	0.106	1	0.584	0.238	418.184	418.184	463.1	37.627	0.498	418.184	0
82083014	P	STACK1	7	506.9	1697.9	308	3.004	10815.6	6720.9	PEN	0.109	0.952	0.596	0.329	336.862	336.862	373.4	38.119	0	336.862	0
82083014	P	STACK2	7	510.1	1697.9	308	3.005	10817.1	6691.7	PEN	0.109	0.959	0.596	0.324	335.532	335.532	371.672	39.358	0	335.532	0
82083014	P	STACK3	7	513.7	1697.9	308	3.005	10818.6	6663.1	PEN	0.109	0.967	0.596	0.32	321.803	321.803	356.181	39.372	0	321.803	0

Table B-18: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 8

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83031211	P	STACK1	6	456.6	1814.9	298	2.001	7204.4	3857.1	PEN	0.082	0.921	0.343	0.216	979.745	979.745	1060.581	69.248	0.489	979.745	0
83031211	P	STACK2	7	454.8	1814.9	298	2.001	7204.4	6691.7	PEN	0.099	0.916	0.343	0.216	949.105	949.105	1046.678	60.297	0.017	949.105	0
83031211	P	STACK3	7	453.4	1814.9	298	2.001	7204.4	6663.1	PEN	0.099	0.911	0.343	0.217	907.798	907.798	1001.036	57.402	0.017	907.798	0
83031210	P	STACK1	8	424.5	1940.7	304	2.792	10050.8	9877.5	PEN	0.072	1	0.346	0.121	626.397	626.397	672.724	32.034	0	626.397	0
83031210	P	STACK2	8	422.4	1920.3	304	2.792	10050.7	9846.7	PEN	0.072	1	0.346	0.122	606.112	606.112	650.873	31.81	0	606.112	0
83031210	P	STACK3	8	426.5	1960.1	304	2.792	10050.9	9816.2	PEN	0.072	1	0.346	0.119	575.179	575.179	617.304	31.118	0	575.179	0
83020709	P	STACK1	7	387.3	1964.3	296	3.74	13462.5	6720.9	PEN	0.046	1	0.424	0.136	535.807	535.807	560.451	27.271	0.015	535.807	0
83020709	P	STACK2	7	383.3	1917.9	296	3.74	13462.5	6691.7	PEN	0.046	1	0.424	0.139	553.672	553.672	579.163	27.039	0.015	553.672	0
83020709	P	STACK3	7	383.5	1919.5	296	3.74	13462.5	6663.1	PEN	0.046	1	0.424	0.138	552.422	552.422	577.852	25.947	0.015	552.422	0
83010711	P	STACK1	8	443.5	1365.7	294	2.238	8057.5	9877.5	PEN	0.085	1	0.304	0.052	374.966	374.966	406.837	33.7	0	374.966	0.00286
83010711	P	STACK2	8	443.7	1365.7	294	2.238	8057.5	9846.7	PEN	0.085	1	0.304	0.052	396.646	396.646	430.471	33.725	0	396.646	0.00286
83010711	P	STACK3	8	443.9	1365.7	294	2.238	8057.5	9816.2	PEN	0.085	1	0.304	0.052	407.504	407.504	442.371	32.661	0	407.504	0.00286
83010715	P	STACK1	7	1755.3	1459.8	311	1.318	4745.3	6720.9	DIR	0.232	0.492	0.397	0.371	436.339	436.339	545.347	75.198	0	436.339	0
83010715	P	STACK2	7	1709	1459.8	311	1.318	4745.2	6691.7	DIR	0.232	0.471	0.397	0.371	397.693	397.693	496.447	70.565	0	397.693	0
83010715	P	STACK3	7	1721.1	1459.8	311	1.318	4745.2	6663.1	DIR	0.232	0.476	0.397	0.371	381.976	381.976	475.974	70.177	0	381.976	0
83031209	P	STACK1	8	412.5	1939.9	297	3.422	12317.7	9877.5	PEN	0.053	1	0.338	0.073	326.599	326.599	343.797	16.597	0	326.599	0.00286
83031209	P	STACK2	8	410.4	1918.1	297	3.422	12317.7	9846.7	PEN	0.052	1	0.338	0.073	341.229	341.229	359.21	16.547	0	341.229	0.00286
83031209	P	STACK3	8	413.2	1946.9	297	3.422	12317.7	9816.2	PEN	0.052	1	0.338	0.073	344.338	344.338	362.474	15.919	0	344.338	0.00286
82062910	P	STACK1	7	521.6	1246	306	2.594	9336.7	6720.9	PEN	0.13	1	0.565	0.29	428.109	428.109	485.475	44.219	0.003	428.109	0
82062910	P	STACK2	7	518.5	1246	306	2.593	9336.3	6691.7	PEN	0.131	1	0.565	0.294	417.064	417.064	473.269	44.331	0.003	417.064	0
82062910	P	STACK3	7	500.2	1246	306	2.592	9332.3	6663.1	PEN	0.135	1	0.565	0.321	369.657	369.657	420.854	40.754	0.003	369.657	0
83020409	P	STACK1	4	222	286.5	304	4.582	16496.9	1396.3	DIR	0.025	0.084	0.479	0.353	91.73	13.307	13.627	0.852	1	91.73	0
83020409	P	STACK2	8	369.5	1920.9	304	4.888	17597	9846.7	PEN	0.044	0.933	0.479	0.249	452.707	452.707	472.703	20.893	0	452.707	0
83020409	P	STACK3	8	374.9	2019	304	4.889	17600.6	9816.2	PEN	0.044	0.954	0.479	0.243	450.783	450.783	470.567	21.732	0	450.783	0
82080512		STACK1	<--- Source is not emitting during this hour																		
82080512	P	STACK2	8	438.7	1001.8	296	2.265	8154.1	9846.7	PEN	0.106	1	0.388	0.055	449.719	449.719	499.336	33.045	0	449.719	0.0022
82080512	P	STACK3	8	455.3	1001.8	296	2.265	8154.1	9816.2	PEN	0.106	1	0.388	0.052	480.358	480.358	533.112	34.554	0	480.358	0.0022
82082317	P	STACK1	6	589.9	1263.1	298	1.384	4983.4	3857.1	PEN	0.186	1	0.387	0.204	735.041	735.041	882.4	88.496	0.489	735.041	0
82082317	P	STACK2	6	598.4	1263.1	298	1.385	4984.8	3832.4	PEN	0.185	1	0.387	0.196	727.478	727.478	872.341	89.013	0.489	727.478	0
82082317		STACK3	<--- Source is not emitting during this hour																		

AECOM Imagine it. Delivered.

Table B-19: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 9

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83010310	P	STACK1	9	453.1	1099.4	16	2.484	8943.3	4449.8	PEN	0.119	1	0.556	0.318	708.681	708.681	795.657	63.269	0	0	0
83010310	P	STACK2	9	449.9	1099.4	16	2.484	8941.8	4391.9	PEN	0.119	1	0.556	0.321	710.674	710.674	797.736	63.385	0.143	710.674	0
83010310	P	STACK3	9	432.6	1099.4	16	2.477	8916.1	4328.4	PEN	0.119	1	0.556	0.354	662.112	662.112	743.51	58.989	0.143	662.112	0
83021110	P	STACK1	9	467.1	1827	17	3.777	13598.9	4449.8	PEN	0.096	0.63	0.765	0.619	563.402	563.402	618.535	46.317	0	0	0
83021110	P	STACK2	9	461.6	1827	17	3.777	13595.6	4391.9	PEN	0.096	0.602	0.766	0.622	530.656	530.656	582.681	43.302	0.143	530.656	0
83021110	P	STACK3	9	468.1	1827	17	3.778	13599.5	4328.4	PEN	0.096	0.634	0.765	0.619	554.475	554.475	608.508	45.468	0.143	554.475	0
83010311	P	STACK1	10	535.9	1024.5	18	1.881	6770.8	2233.8	PEN	0.299	0.573	0.697	0.643	639.636	639.636	856.123	131.893	0	0	0
83010311	P	STACK2	10	532.4	1024.5	18	1.863	6706	2174.4	PEN	0.299	0.557	0.699	0.635	617.402	617.402	826.974	126.957	0.821	617.402	0
83010311	P	STACK3	10	523.8	1024.5	18	1.862	6703.2	2109.7	PEN	0.301	0.518	0.701	0.639	533.093	533.093	715.301	109.486	0.817	533.093	0
82062209	P	STACK1	9	509.1	1290.5	17	2.846	10246.4	4449.8	PEN	0.147	0.999	0.731	0.479	443.895	443.895	512.005	49.837	0	0	0
82062209	P	STACK2	9	508.5	1290.5	17	2.847	10249.5	4391.9	PEN	0.147	0.998	0.731	0.479	447.218	447.218	515.722	50.107	0.143	447.218	0
82062209	P	STACK3	9	495.9	1290.5	17	2.833	10198.4	4328.4	PEN	0.15	0.97	0.732	0.497	416.314	416.314	481.338	46.708	0.143	416.314	0
83012511	P	STACK1	9	586.2	1689	25	2.047	7367.6	4449.8	PEN	0.134	0.859	0.484	0.364	405.787	405.787	460.022	55.264	0	0	0
83012511	P	STACK2	9	588.4	1689	25	2.046	7364.8	4391.9	PEN	0.134	0.864	0.484	0.361	417.276	417.276	473.056	56.113	0.013	417.276	0
83012511	P	STACK3	9	593.7	1689	25	2.046	7366.6	4328.4	PEN	0.133	0.876	0.484	0.356	415.833	415.833	471.335	55.314	0.014	415.833	0
82112113	P	STACK1	9	427.6	1698.8	10	4	14399.1	4449.8	PEN	0.081	0.63	0.725	0.544	437.063	437.063	472.468	35.903	0	0	0
82112113	P	STACK2	9	422.7	1617.3	10	3.997	14390.8	4391.9	PEN	0.081	0.601	0.726	0.546	398.317	398.317	430.634	32.997	0	0	0
82112113	P	STACK3	9	420.8	1585.3	10	3.997	14387.5	4328.4	PEN	0.081	0.589	0.726	0.547	382.779	382.779	413.789	32.04	0	0	0
83021211	P	STACK1	10	553.5	703	29	1.528	5502	2233.8	PEN	0.493	0.797	0.745	0.667	543.791	543.791	866.373	211.427	0	0	0
83021211	P	STACK2	10	547.2	703	29	1.528	5501.5	2174.4	PEN	0.495	0.779	0.747	0.672	525.118	525.118	840.546	203.738	0.05	525.118	0
83021211	P	STACK3	10	554.9	703	29	1.528	5502.1	2109.7	PEN	0.491	0.801	0.744	0.666	551.503	551.503	878.935	212.574	0.05	551.503	0
82043012	P	STACK1	9	526.8	1694	9	2.784	10021.3	4449.8	PEN	0.084	0.838	0.499	0.38	396.723	396.723	430.122	34.581	0	0	0
82043012	P	STACK2	9	541.3	1829.5	9	2.802	10087.8	4391.9	PEN	0.083	0.876	0.499	0.367	420.408	420.408	454.969	37.058	0	0	0
82043012	P	STACK3	9	494.1	1388.2	9	2.684	9663.6	4328.4	PEN	0.09	0.733	0.499	0.396	314.012	314.012	342.181	28.547	0	0	0
82102411	P	STACK1	9	571.3	1051.6	19	1.864	6710	4449.8	PEN	0.232	0.975	0.604	0.462	555.725	555.725	699.08	80.768	0	0	0
82102411		STACK2	<--- Source is not emitting during this hour																		
82102411	P	STACK3	9	572.3	1051.6	19	1.862	6703.2	4328.4	PEN	0.232	0.977	0.604	0.463	558.549	558.549	702.404	81.043	0.145	558.549	0
83021212	P	STACK1	9	575.2	1283.4	27	2.723	9803.6	4449.8	PEN	0.224	0.593	0.858	0.775	352.919	352.919	436.449	63.572	0	0	0
83021212	P	STACK2	9	567.5	1283.4	27	2.722	9799.7	4391.9	PEN	0.225	0.563	0.861	0.779	330.431	330.431	409.416	58.966	0.006	330.431	0
83021212	P	STACK3	9	574.5	1283.4	27	2.723	9803.3	4328.4	PEN	0.224	0.59	0.859	0.775	353.542	353.542	437.405	62.609	0.005	353.542	0

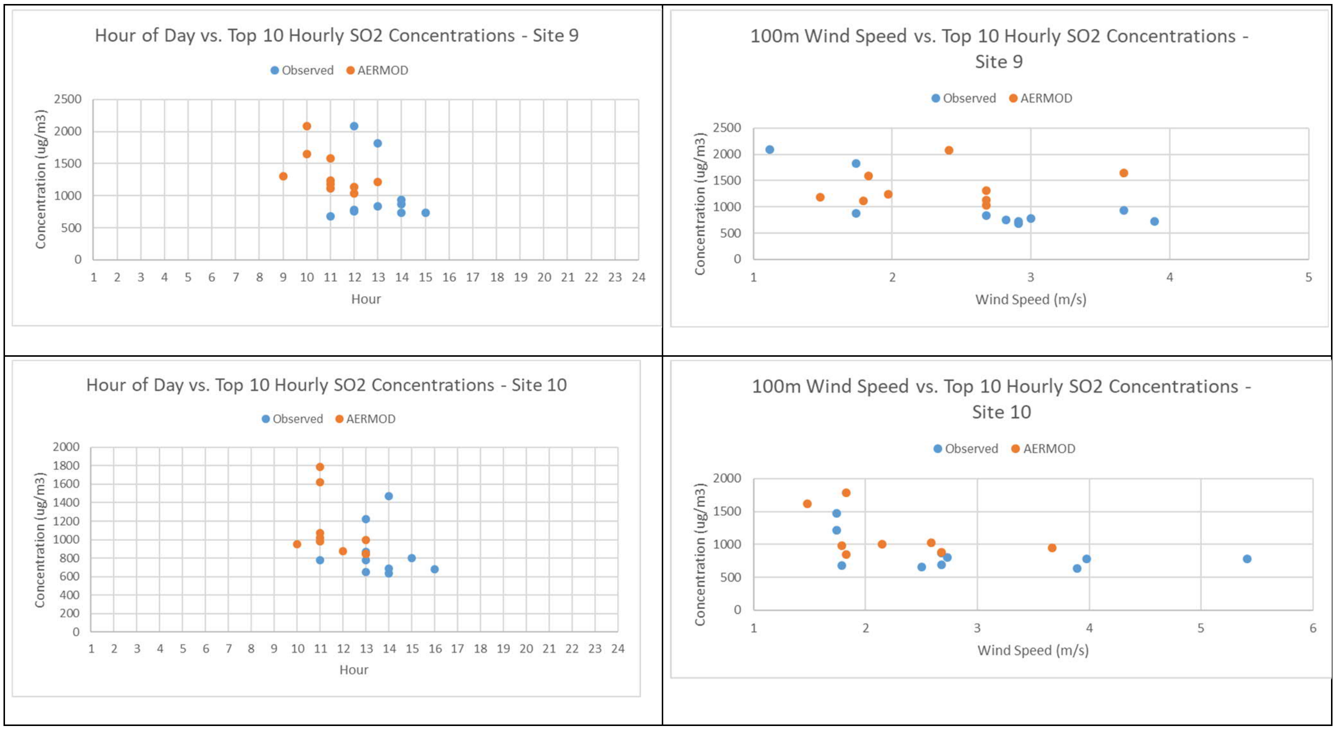
Table B-20: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Baldwin Database Site 10

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
83010311	P	STACK1	10	535.9	1024.5	18	1.881	6770.8	2233.8	PEN	0.299	0.573	0.697	0.643	639.636	639.636	856.123	131.893	0	0	0
83010311	P	STACK2	10	532.4	1024.5	18	1.863	6706	2174.4	PEN	0.299	0.557	0.699	0.635	617.402	617.402	826.974	126.957	0.821	617.402	0
83010311	P	STACK3	10	523.8	1024.5	18	1.862	6703.2	2109.7	PEN	0.301	0.518	0.701	0.639	533.093	533.093	715.301	109.486	0.817	533.093	0
83021211	P	STACK1	10	553.5	703	29	1.528	5502	2233.8	PEN	0.493	0.797	0.745	0.667	543.791	543.791	866.373	211.427	0	0	0
83021211	P	STACK2	10	547.2	703	29	1.528	5501.5	2174.4	PEN	0.495	0.779	0.747	0.672	525.118	525.118	840.546	203.738	0.05	525.118	0
83021211	P	STACK3	10	554.9	703	29	1.528	5502.1	2109.7	PEN	0.491	0.801	0.744	0.666	551.503	551.503	878.935	212.574	0.05	551.503	0
82112111	P	STACK1	10	395.4	1709.9	5	3.46	12455.6	2233.8	PEN	0.061	0.828	0.58	0.43	395.264	395.264	419.167	28.514	0	0	0
82112111	P	STACK2	10	388.6	1603.6	5	3.458	12447.3	2174.4	PEN	0.061	0.795	0.58	0.434	351.584	351.584	372.862	25.651	0	0	0
82112111	P	STACK3	10	388	1595.2	5	3.457	12446.6	2109.7	PEN	0.061	0.792	0.58	0.434	325.727	325.727	345.323	23.992	0	0	0
82060511	P	STACK1	10	471	1279	6	2.735	9845.6	2233.8	PEN	0.114	0.994	0.624	0.376	536.004	536.004	597.803	53.544	0	0	0
82060511		STACK2	<--- Source is not emitting during this hour																		
82060511	P	STACK3	10	465.3	1279	6	2.734	9844.2	2109.7	PEN	0.113	0.98	0.624	0.383	486.599	486.599	542.606	49.136	0	0	0
82121213	P	STACK1	10	510.3	1276.5	354	2.279	8203.8	2233.8	PEN	0.16	0.921	0.621	0.383	359.495	359.495	414.241	71.962	0	0	0
82121213	P	STACK2	10	501.2	1276.5	354	2.278	8200	2174.4	PEN	0.16	0.897	0.621	0.394	334.553	334.553	385.346	68.069	0	0	0
82121213	P	STACK3	10	496.6	1276.5	354	2.277	8197.8	2109.7	PEN	0.16	0.885	0.621	0.4	305.83	305.83	352.054	63.144	0	0	0
82102411	P	STACK1	9	571.3	1051.6	19	1.864	6710	4449.8	PEN	0.232	0.975	0.604	0.462	555.725	555.725	699.08	80.768	0	0	0
82102411		STACK2	<--- Source is not emitting during this hour																		
82102411	P	STACK3	9	572.3	1051.6	19	1.862	6703.2	4328.4	PEN	0.232	0.977	0.604	0.463	558.549	558.549	702.404	81.043	0.145	558.549	0
83021110	P	STACK1	9	467.1	1827	17	3.777	13598.9	4449.8	PEN	0.096	0.63	0.765	0.619	563.402	563.402	618.535	46.317	0	0	0
83021110	P	STACK2	9	461.6	1827	17	3.777	13595.6	4391.9	PEN	0.096	0.602	0.766	0.622	530.656	530.656	582.681	43.302	0.143	530.656	0
83021110	P	STACK3	9	468.1	1827	17	3.778	13599.5	4328.4	PEN	0.096	0.634	0.765	0.619	554.475	554.475	608.508	45.468	0.143	554.475	0
83021212	P	STACK1	9	575.2	1283.4	27	2.723	9803.6	4449.8	PEN	0.224	0.593	0.858	0.775	352.919	352.919	436.449	63.572	0	0	0
83021212	P	STACK2	9	567.5	1283.4	27	2.722	9799.7	4391.9	PEN	0.225	0.563	0.861	0.779	330.431	330.431	409.416	58.966	0.006	330.431	0
83021212	P	STACK3	9	574.5	1283.4	27	2.723	9803.3	4328.4	PEN	0.224	0.59	0.859	0.775	353.542	353.542	437.405	62.609	0.005	353.542	0
83010313	P	STACK1	10	1213	1264.6	3	1.894	6818.4	2233.8	DIR	0.408	0.227	0.845	0.79	315.18	315.18	477.271	79.578	0	0	0
83010313	P	STACK2	10	1122.7	1264.6	3	1.895	6823.1	2174.4	DIR	0.408	0.185	0.845	0.79	267.466	267.466	405.465	67.158	0	0	0
83010313	P	STACK3	10	1126.9	1264.6	3	1.896	6827.3	2109.7	DIR	0.408	0.186	0.845	0.79	262.624	262.624	397.7	66.357	0	0	0
82112113	P	STACK1	9	427.6	1698.8	10	4	14399.1	4449.8	PEN	0.081	0.63	0.725	0.544	437.063	437.063	472.468	35.903	0	0	0
82112113	P	STACK2	9	422.7	1617.3	10	3.997	14390.8	4391.9	PEN	0.081	0.601	0.726	0.546	398.317	398.317	430.634	32.997	0	0	0
82112113	P	STACK3	9	420.8	1585.3	10	3.997	14387.5	4328.4	PEN	0.081	0.589	0.726	0.547	382.779	382.779	413.789	32.04	0	0	0

Figure B-1: Top 10 Concentrations vs. Hour of Day and Wind Speed – Sites 1 through 4

Figure B-2: Top 10 Concentrations vs. Hour of Day and Wind Speed – Sites 5 through 8

Figure B-3: Top 10 Concentrations vs. Hour of Day and Wind Speed – Sites 9 and 10



APPENDIX C: Labadie Tables and Plots

Table C-1: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Valley Site

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	18121013	0.22	1.06	-7.8	N.A.	244	361	N.A.	0.03	-9.99
2	17090210	0.17	1.44	-2.5	N.A.	174	575	N.A.	0.2	-9.99
3	18060610	0.22	1.17	-7.2	N.A.	252	420	N.A.	0.2	-9.99
4	17060511	0.19	1.23	-4.3	N.A.	203	450	N.A.	0.2	-9.99
5	18121016	0.16	0.52	-31	N.A.	161	434	N.A.	0.03	-9.99
6	17092910	0.25	1.26	-9.3	N.A.	301	473	N.A.	0.2	-9.99
7	17051109	0.07	0.6	-1.5	N.A.	49	310	N.A.	0.04	-9.99
8	17050910	0.33	1.1	-24.5	N.A.	460	357	N.A.	0.04	-9.99
9	17051012	0.21	1.22	-5.3	N.A.	231	417	N.A.	0.04	-9.99
10	18060609	0.17	0.95	-4.4	N.A.	171	299	N.A.	0.2	-9.99

Table C-2: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Northwest Site

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	18022211	0.16	0.77	-9.1	N.A.	159	374	N.A.	0.03	-9.99
2	19062715	0.16	0.7	-15.8	N.A.	153	532	N.A.	0.2	-9.99
3	18060609	0.17	0.95	-4.4	N.A.	171	299	N.A.	0.2	-9.99
4	19111611	0.17	0.86	-6.8	N.A.	174	325	N.A.	0.2	-9.99
5	19111515	0.15	0.74	-7.1	N.A.	134	368	N.A.	0.2	-9.99
6	19061111	0.19	1.04	-6.8	N.A.	203	431	N.A.	0.2	-9.99
7	18021312	0.17	0.96	-3.6	N.A.	166	267	N.A.	0.03	-9.99
8	17111611	0.24	1.24	-10.5	N.A.	283	584	N.A.	0.176	-9.99
9	19072111	0.18	1.07	-6	N.A.	188	489	N.A.	0.2	-9.99
10	19062813	0.17	1.28	-4.3	N.A.	176	730	N.A.	0.204	-9.99

Table C-3: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Southwest Site

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	19020112	0.22	0.92	-11.9	N.A.	247	346	N.A.	0.03	-9.99
2	19111516	0.1	0.47	-9.9	N.A.	81	370	N.A.	0.2	-9.99
3	17022310	0.13	0.95	-2.2	N.A.	117	322	N.A.	0.03	-9.99
4	19012712	0.21	0.84	-16.3	N.A.	230	422	N.A.	0.03	-9.99
5	17052708	0.12	1.04	-1.8	N.A.	97	489	N.A.	0.04	-9.99
6	17052310	0.12	0.72	-6	N.A.	104	487	N.A.	0.04	-9.99
7	17022311	0.13	1.26	-1.2	N.A.	110	451	N.A.	0.03	-9.99
8	18041709	0.16	1.26	-3.7	N.A.	153	734	N.A.	0.04	-9.99
9	18010513	0.23	0.99	-15.8	N.A.	257	544	N.A.	0.03	-9.99
10	19052610	0.21	0.93	-11.3	N.A.	226	405	N.A.	0.04	-9.99

Table C-4: Meteorological Parameters for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database North Site

Rank	YYMMDDHH	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
1	19020114	0.12	0.97	-2.1	N.A.	104	414	N.A.	0.03	-9.99
2	19020115	0.13	0.9	-3.6	N.A.	117	437	N.A.	0.03	-9.99
3	18071912	0.23	1.14	-10	N.A.	271	463	N.A.	0.092	-9.99
4	17051510	0.17	1.24	-3.3	N.A.	172	504	N.A.	0.04	-9.99
5	17053010	0.09	1.44	-1	N.A.	68	776	N.A.	0.04	-9.99
6	17060410	0.16	1.21	-3.2	N.A.	152	567	N.A.	0.2	-9.99
7	19062711	0.11	1	-1.2	N.A.	83	394	N.A.	0.2	-9.99
8	18060609	0.17	0.95	-4.4	N.A.	171	299	N.A.	0.2	-9.99
9	19120713	0.14	0.9	-3.8	N.A.	129	382	N.A.	0.03	-9.99
10	17043015	0.1	0.71	-3	N.A.	77	398	N.A.	0.04	-9.99

Table C-5: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Valley Site

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
18121013	P	LAB34	1	475.3	1483.8	245	2.522	9079.9	3724.9	PEN	0.174	0.911	0.711	0.453	53.331	53.331	63.14	6.767	0.3	53.331	0
18121013	P	LABADIE1	1	467.9	1483.8	245	2.524	9086	3765.4	PEN	0.175	0.887	0.712	0.457	50.644	50.644	59.945	6.732	0.286	50.644	0
18121013	P	LABADIE2	1	475.5	1483.8	245	2.522	9079.7	3747.2	PEN	0.174	0.912	0.71	0.453	54.016	54.016	63.917	7.041	0.293	54.016	0
18121013	P	LABADIE5	1	18.8	52.2	241	2.488	8957.8	3723	DIR	0.185	0.001	0.727	0.499	0	0	0	0	0	0	0
17090210	P	LAB34	1	698.9	1073	245	1.489	5360.2	3724.9	PEN	0.433	0.61	0.594	0.587	80.84	80.84	126.836	20.557	0.214	80.84	0
17090210	P	LABADIE1	1	1380.1	1073	245	1.433	5157.1	3765.4	IND	0.492	0.405	0.613	0.633	36.269	36.269	61.533	10.209	0.183	36.269	0
17090210	P	LABADIE2	1	1446	1073	245	1.433	5157.1	3747.2	IND	0.483	0.441	0.613	0.633	41.596	41.596	69.69	11.484	0.197	41.596	0
17090210	P	LABADIE5	1	33.6	51.2	285	1.154	4155.6	3723	DIR	0.581	0	0.613	0.606	0	0	0	0	0	0	0
18060610	P	LAB34	1	596.3	852.4	236	1.537	5534.1	3724.9	PEN	0.457	0.946	0.704	0.493	74.976	74.976	118.695	22.934	0.004	74.976	0
18060610	P	LABADIE1	1	537.3	852.4	236	1.506	5422.7	3765.4	PEN	0.539	0.797	0.717	0.523	40.048	40.048	70.078	14.399	0.004	40.048	0
18060610	P	LABADIE2	1	541.6	852.4	236	1.508	5430.3	3747.2	PEN	0.533	0.811	0.716	0.521	41.303	41.303	71.865	14.479	0.004	41.303	0
18060610	P	LABADIE5	3	24.6	50.8	3	1.105	3977.3	4310.6	DIR	0.896	0.001	0.737	0.587	0	0	0	0	0	0	0
17060511	P	LAB34	1	746.9	1017.3	244	1.659	5973.9	3724.9	PEN	0.305	1	0.629	0.358	51.545	51.545	69.748	10.15	0.314	51.545	0
17060511	P	LABADIE1	1	645.1	1017.3	244	1.617	5819.6	3765.4	PEN	0.378	0.934	0.68	0.484	33.33	33.33	48.858	7.834	0.314	33.33	0
17060511	P	LABADIE2	1	647.8	1017.3	244	1.621	5834.3	3747.2	PEN	0.375	0.938	0.679	0.482	32.834	32.834	47.981	7.584	0.314	32.834	0
17060511	P	LABADIE5	1	28.6	50.8	244	1.493	5373.7	3723	DIR	0.482	0.002	0.722	0.549	0	0	0	0	0	0	0
18121016	P	LAB34	1	554.9	2020.9	255	1.579	5685.7	3724.9	PEN	0.18	0.784	0.457	0.205	35.476	35.476	42.22	4.708	0.458	35.476	0
18121016	P	LABADIE1	1	546.5	1921.8	255	1.585	5707.2	3765.4	PEN	0.178	0.757	0.457	0.209	36.478	36.478	43.371	4.601	0.452	36.478	0
18121016	P	LABADIE2	1	555.5	2027.6	255	1.579	5685.6	3747.2	PEN	0.18	0.786	0.457	0.205	37.164	37.164	44.27	4.795	0.455	37.164	0
18121016	P	LABADIE5	1	20.9	52.1	257	1.835	6607.5	3723	DIR	0.144	0.001	0.457	0.236	0	0	0	0	0	0	0
17092910	P	LAB34	1	688.8	1884.2	252	2.829	10183.8	3724.9	PEN	0.113	0.937	0.611	0.382	41.079	41.079	45.79	4.026	0.462	41.079	0
17092910	P	LABADIE1	1	608.3	1830.9	252	2.709	9753.1	3765.4	PEN	0.144	0.766	0.644	0.461	34.87	34.87	40.12	3.755	0.46	34.87	0
17092910	P	LABADIE2	1	604.4	1794.1	252	2.7	9720.6	3747.2	PEN	0.146	0.755	0.645	0.464	31.703	31.703	36.536	3.442	0.461	31.703	0
17092910	P	LABADIE5	2	22.3	51.2	217	2.202	7928.1	3346.3	DIR	0.192	0.001	0.669	0.504	0	0	0	0	0	0	0
17051109	P	LAB34	1	688.7	506.5	263	0.755	2719.6	3724.9	PEN	0.542	1	0.384	0.08	20.977	20.977	37.088	7.382	0.019	20.977	0
17051109	P	LABADIE1	1	606.4	506.5	263	0.755	2718.6	3765.4	PEN	0.543	1	0.384	0.149	44.909	44.909	81.805	13.858	0.018	44.909	0
17051109	P	LABADIE2	1	616.6	506.5	263	0.755	2719	3747.2	PEN	0.543	1	0.384	0.137	40.569	40.569	73.419	12.891	0.018	40.569	0
17051109	P	LABADIE5	1	46.2	51.2	263	0.615	2214.9	3723	IND	0.625	0.005	0.384	0.253	0	0	0	0	0	0	0
17050910	P	LAB34	1	534.8	1944.4	250	4.253	15309.5	3724.9	PEN	0.12	0.566	0.784	0.498	37.365	37.365	42.009	3.468	0.461	37.365	0
17050910	P	LABADIE1	1	533.2	1919.5	250	4.251	15303.4	3765.4	PEN	0.122	0.559	0.786	0.504	31.369	31.369	35.303	2.946	0.461	31.369	0
17050910	P	LABADIE2	1	523.5	1767.4	250	4.244	15280	3747.2	PEN	0.127	0.51	0.793	0.527	32.155	32.155	36.396	3.035	0.461	32.155	0
17050910	P	LABADIE5	1	15	50.9	258	3.086	11108.6	3723	DIR	0.177	0	0.887	0.733	0	0	0	0	0	0	0
17051012	P	LAB34	1	574.4	1644.6	244	4.533	16319.3	3724.9	PEN	0.08	0.911	0.771	0.624	39.664	39.664	42.79	3.631	0.354	39.664	0
17051012	P	LABADIE1	1	535.4	1644.6	244	4.134	14882.3	3765.4	PEN	0.108	0.806	0.793	0.68	30.389	30.389	33.666	3.454	0.339	30.389	0
17051012	P	LABADIE2	1	537.6	1644.6	244	4.16	14975.6	3747.2	PEN	0.107	0.813	0.792	0.676	32.549	32.549	36.012	3.504	0.344	32.549	0
17051012	P	LABADIE5	4	19.8	50.7	200	2.613	9407.9	3858.4	DIR	0.193	0.001	0.825	0.729	0	0	0	0	0	0	0
18060609	P	LAB34	3	706.4	336.4	68	0.532	1914.4	4312.9	PEN	1	1	0.6	0.098	40.85	40.85	65.308	40.85	PLUME OUT	OF WAKE	0
18060609	P	LABADIE1	2	598.5	336.4	68	0.542	1951.6	3203.1	PEN	1	1	0.612	0.207	36.971	36.971	7.96	36.971	PLUME OUT	OF WAKE	0
18060609	P	LABADIE2	2	605.7	336.4	68	0.539	1941.4	3259	PEN	1	1	0.611	0.195	36.188	36.188	6.502	36.188	PLUME OUT	OF WAKE	0
18060609	P	LABADIE5	2	31.1	50.9	39	0.689	2479.1	3346.3	DIR	1	0.002	0.652	0.488	0	0	0	0	0	0	0

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Table C-6: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Northwest Site

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
18022211	P	LAB34	2	586.9	903.6	116	0.916	3298.3	3340.2	PEN	0.727	1	0.548	0.26	67.635	67.635	153.756	35.339	0.001	67.635	0
18022211	P	LABADIE1	2	510.8	903.6	116	0.952	3428.8	3203.1	PEN	0.667	0.945	0.548	0.303	44.251	44.251	92.432	20.203	0.001	44.251	0
18022211	P	LABADIE2	2	514.2	903.6	116	0.952	3425.9	3259	PEN	0.67	0.954	0.548	0.302	45.333	45.333	94.975	20.83	0.001	45.333	0
18022211	P	LABADIE5	3	21.7	52.2	31	1.012	3641.7	4310.6	DIR	0.607	0.001	0.548	0.354	0	0	0	0	0	0	0
19062715	P	LAB34	2	827.2	1431.6	142	1.358	4889.8	3340.2	PEN	0.302	0.974	0.512	0.3	50.649	50.649	67.773	11.124	PLUME OUT	OF WAKE	0
19062715	P	LABADIE1	2	724.7	1431.6	142	1.429	5146	3203.1	PEN	0.268	0.821	0.512	0.377	39.469	39.469	50.907	8.166	PLUME OUT	OF WAKE	0
19062715	P	LABADIE2	2	702.8	1431.6	142	1.433	5159.7	3259	PEN	0.265	0.776	0.512	0.392	35.835	35.835	46.109	7.318	PLUME OUT	OF WAKE	0
19062715	P	LABADIE5	2	28	50.6	157	1.569	5647.5	3346.3	DIR	0.232	0.001	0.512	0.441	0	0	0	0	0	0	0
18060609	P	LAB34	3	706.4	336.4	68	0.532	1914.4	4312.9	PEN	1	1	0.6	0.098	40.85	40.85	65.308	40.85	PLUME OUT	OF WAKE	0
18060609	P	LABADIE1	2	598.5	336.4	68	0.542	1951.6	3203.1	PEN	1	1	0.612	0.207	36.971	36.971	7.96	36.971	PLUME OUT	OF WAKE	0
18060609	P	LABADIE2	2	605.7	336.4	68	0.539	1941.4	3259	PEN	1	1	0.611	0.195	36.188	36.188	6.502	36.188	PLUME OUT	OF WAKE	0
18060609	P	LABADIE5	2	31.1	50.9	39	0.689	2479.1	3346.3	DIR	1	0.002	0.652	0.488	0	0	0	0	0	0	0
19111611	P	LAB34	2	439.9	1692.6	123	2.559	9212.4	3340.2	PEN	0.078	1	0.459	0.309	50.433	50.433	54.274	5.217	PLUME OUT	OF WAKE	0
19111611	P	LABADIE1	2	423.4	1632.4	123	2.521	9074.8	3203.1	PEN	0.081	0.957	0.459	0.324	50.252	50.252	54.252	5.011	0.046	50.252	0
19111611		LABADIE2 <--- Source is not emitting during this hour																			
19111611	P	LABADIE5	3	29.1	52	28	2.207	7944.2	4310.6	DIR	0.107	0.002	0.46	0.373	0	0	0	0	0	0	0
19111515	P	LAB34	2	602.4	685.3	135	1.484	5341.5	3340.2	PEN	0.246	1	0.499	0.237	47.729	47.729	60.871	7.504	0.18	47.729	0
19111515	P	LABADIE1	2	590	685.3	135	1.445	5200.6	3203.1	PEN	0.258	1	0.499	0.25	48.339	48.339	62.389	7.947	0.224	48.339	0
19111515		LABADIE2 <--- Source is not emitting during this hour																			
19111515	P	LABADIE5	4	33.2	51.8	54	0.699	2517.9	3858.4	DIR	0.999	0.001	0.499	0.394	0	0	0	0	0	0	0
19061111	P	LAB34	3	985.4	408.8	290	0.521	1873.9	4312.9	PEN	1	1	0.627	0.153	27.882	27.882	0	27.882	PLUME OUT	OF WAKE	0
19061111	P	LABADIE1	2	816.9	408.8	290	0.522	1879.7	3203.1	PEN	1	1	0.667	0.388	30.943	30.943	0	30.943	PLUME OUT	OF WAKE	0
19061111	P	LABADIE2	2	847.1	408.8	290	0.518	1866.5	3259	PEN	1	1	0.657	0.333	30.062	30.062	0	30.062	PLUME OUT	OF WAKE	0
19061111	P	LABADIE5	4	27	50.9	247	0.974	3506.5	3858.4	DIR	1	0.002	0.718	0.627	0	0	0	0	0	0	0
18021312	P	LAB34	3	674.1	412.9	62	0.56	2016	4312.9	PEN	1	1	0.912	0.076	32.815	32.815	47.257	32.815	PLUME OUT	OF WAKE	0
18021312	P	LABADIE1	2	566	412.9	62	0.559	2014	3203.1	PEN	1	1	0.921	0.152	32.148	32.148	0.975	32.148	PLUME OUT	OF WAKE	0
18021312	P	LABADIE2	2	569.9	412.9	62	0.559	2014.2	3259	PEN	1	1	0.92	0.148	31.06	31.06	0.816	31.06	PLUME OUT	OF WAKE	0
18021312	P	LABADIE5	2	23	52.1	158	0.918	3303.8	3346.3	DIR	1	0.002	0.998	0.515	0	0	0	0	0	0	0
17111611	P	LAB34	2	1797.1	988.7	123	1.295	4662.2	3340.2	IND	0.724	0.457	0.736	0.594	40.858	40.858	94.089	20.571	0.328	40.858	0
17111611	P	LABADIE1	2	1473.6	988.7	123	1.295	4662.2	3203.1	IND	0.721	0.308	0.736	0.594	25.873	25.873	60.324	12.538	0.263	25.873	0
17111611	P	LABADIE2	2	1311.1	988.7	123	1.295	4662.2	3259	IND	0.719	0.233	0.736	0.594	19.791	19.791	46.508	9.324	0.29	19.791	0
17111611	P	LABADIE5	2	22.5	52.1	73	1.245	4480.3	3346.3	DIR	0.709	0	0.736	0.585	0	0	0	0	0	0	0
19072111	P	LAB34	2	722.3	852.4	107	1.162	4183	3340.2	PEN	0.696	0.943	0.694	0.547	40.827	40.827	81.568	23.019	PLUME OUT	OF WAKE	0
19072111	P	LABADIE1	2	642.4	852.4	107	1.226	4412.7	3203.1	PEN	0.581	0.79	0.705	0.591	23.605	23.605	40.679	11.282	PLUME OUT	OF WAKE	0
19072111	P	LABADIE2	2	617	852.4	107	1.25	4498.4	3259	PEN	0.539	0.722	0.709	0.605	17.993	17.993	29.361	8.271	PLUME OUT	OF WAKE	0
19072111	P	LABADIE5	2	28.2	50.6	337	2.163	7786.9	3346.3	DIR	0.238	0.001	0.724	0.653	0	0	0	0	0	0	0
19062813	P	LAB34	2	878.2	1521.9	125	1.992	7171.3	3340.2	PEN	0.344	0.547	0.805	0.729	39.124	39.124	55.116	8.688	0.523	39.124	0
19062813	P	LABADIE1	2	1463.3	1521.9	125	1.696	6105.4	3203.1	IND	0.35	0.361	0.824	0.781	23.507	23.507	33.395	5.113	0.478	23.507	0
19062813	P	LABADIE2	2	1348.9	1521.9	125	1.696	6105.4	3259	IND	0.35	0.302	0.824	0.781	19.918	19.918	28.357	4.275	0.508	19.918	0
19062813	P	LABADIE5	2	31	50.5	120	2.006	7221.4	3346.3	DIR	0.35	0	0.824	0.76	0	0	0	0	0	0	0

Table C-7: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database Southwest Site

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
19020112	P	LAB34	3	593.6	1121.3	24	0.865	3113.5	4312.9	PEN	0.771	1	0.532	0.227	53.665	53.665	135.778	29.213	0.208	53.665	0
19020112	P	LABADIE1	3	516.8	1121.3	24	0.981	3532.2	4371.5	PEN	0.617	1	0.536	0.269	43.356	43.356	86.75	16.421	0.182	43.356	0
19020112	P	LABADIE2	3	528.3	1121.3	24	0.973	3502.4	4348.5	PEN	0.626	1	0.535	0.264	44.103	44.103	89.217	17.122	0.192	44.103	0
19020112	P	LABADIE5	4	18.3	52.1	61	1.597	5749.9	3858.4	DIR	0.315	0.001	0.543	0.336	0	0	0	0	0	0	0
19111516	P	LAB34	3	518.7	947.1	40	1.045	3762.4	4312.9	PEN	0.441	0.983	0.472	0.271	71.335	71.335	113.691	17.599	0.008	71.335	0
19111516	P	LABADIE1	3	512.3	947.1	40	1.045	3761.7	4371.5	PEN	0.446	0.968	0.472	0.273	61.912	61.912	98.797	16.041	0.007	61.912	0
19111516		LABADIE2	<--- Source is not emitting during this hour																		
19111516	P	LABADIE5	2	41	51.8	353	0.763	2747.9	3346.3	DIR	0.776	0.002	0.472	0.319	0	0	0	0	0	0	0
17022310	P	LAB34	3	635.4	1006.6	27	1.544	5556.7	4312.9	PEN	0.196	1	0.449	0.121	26.157	26.157	31.732	3.287	0.245	26.157	0
17022310	P	LABADIE1	3	546.1	1006.6	27	1.54	5544.1	4371.5	PEN	0.209	1	0.465	0.235	50.948	50.948	62.702	6.438	0.243	50.948	0
17022310	P	LABADIE2	3	554.1	1006.6	27	1.541	5547.5	4348.5	PEN	0.207	1	0.463	0.222	51.313	51.313	63.023	6.493	0.244	51.313	0
17022310	P	LABADIE5	3	27.3	51.5	27	1.475	5309.5	4310.6	DIR	0.248	0.002	0.492	0.392	0	0	0	0	0	0	0
19012712	P	LAB34	3	520.7	2364	28	2.874	10345.7	4312.9	PEN	0.15	0.729	0.667	0.348	62.147	62.147	71.987	6.481	0.257	62.147	0
19012712	P	LABADIE1	3	492	1905.1	28	2.752	9908.9	4371.5	PEN	0.169	0.602	0.667	0.362	47.698	47.698	56.357	5.21	0.238	47.698	0
19012712		LABADIE2	<--- Source is not emitting during this hour																		
19012712	P	LABADIE5	3	18.5	52.4	35	2.087	7514.3	4310.6	DIR	0.223	0	0.667	0.39	0	0	0	0	0	0	0
17052708	P	LAB34	3	633.9	1010.7	7	1.353	4869.4	4312.9	PEN	0.307	0.769	0.446	0.453	46.505	46.505	59.013	18.326	PLUME OUT	OF WAKE	0
17052708	P	LABADIE1	3	580.1	1010.7	7	1.33	4787.2	4371.5	PEN	0.362	0.597	0.452	0.474	30.75	30.75	41.972	10.93	PLUME OUT	OF WAKE	0
17052708	P	LABADIE2	3	582.8	1010.7	7	1.331	4791.7	4348.5	PEN	0.358	0.607	0.452	0.473	30.092	30.092	40.673	11.142	PLUME OUT	OF WAKE	0
17052708	P	LABADIE5	2	31.8	51	62	0.932	3354.4	3346.3	DIR	0.504	0.001	0.458	0.488	0	0	0	0	0	0	0
17052310	P	LAB34	3	864.3	977.2	20	0.866	3117.6	4312.9	PEN	0.548	1	0.442	0.196	40.736	40.736	73.588	13.638	0.021	40.736	0
17052310	P	LABADIE1	3	728.4	977.2	20	0.854	3074.8	4371.5	PEN	0.564	0.957	0.442	0.295	30.541	30.541	56.951	10.093	0.021	30.541	0
17052310	P	LABADIE2	3	739.4	977.2	20	0.854	3072.6	4348.5	PEN	0.564	0.973	0.442	0.291	31.714	31.714	59.037	10.575	0.021	31.714	0
17052310	P	LABADIE5	1	27.4	51.3	279	0.898	3231.5	3723	DIR	0.509	0.001	0.442	0.349	0	0	0	0	0	0	0
17022311	P	LAB34	3	681.9	816.4	8	1.32	4752	4312.9	PEN	0.366	0.99	0.545	0.481	46.23	46.23	63.525	16.266	PLUME OUT	OF WAKE	0
17022311	P	LABADIE1	3	612.2	816.4	8	1.317	4742.9	4371.5	PEN	0.394	0.864	0.56	0.52	28.327	28.327	40.653	9.37	PLUME OUT	OF WAKE	0
17022311	P	LABADIE2	3	618.4	816.4	8	1.318	4743.8	4348.5	PEN	0.391	0.877	0.558	0.517	30.068	30.068	42.81	10.245	PLUME OUT	OF WAKE	0
17022311	P	LABADIE5	3	30	51.3	8	1.283	4620.1	4310.6	DIR	0.45	0.001	0.594	0.588	0	0	0	0	0	0	0
18041709	P	LAB34	3	2027.9	2261.9	32	2.032	7316	4312.9	IND	0.162	0.292	0.558	0.602	49.115	49.115	57.459	5.926	0.258	49.115	0
18041709	P	LABADIE1	3	1432.4	1891.4	32	2.032	7316	4371.5	IND	0.168	0.158	0.558	0.602	26.484	26.484	31.179	3.221	0.247	26.484	0
18041709	P	LABADIE2	3	1567.7	2029	32	2.032	7316	4348.5	IND	0.167	0.181	0.558	0.602	28.32	28.32	33.306	3.43	0.251	28.32	0
18041709	P	LABADIE5	3	24.5	52	24	2.017	7260.3	4310.6	DIR	0.174	0	0.558	0.598	0	0	0	0	0	0	0
18010513	P	LAB34	3	630.3	2250.5	33	2.916	10497.8	4312.9	PEN	0.149	0.515	0.734	0.544	44.619	44.619	51.547	5.037	0.24	44.619	0
18010513	P	LABADIE1	3	1087	1929.5	33	2.925	10528.7	4371.5	IND	0.152	0.34	0.738	0.573	25.852	25.852	29.965	2.964	0.241	25.852	0
18010513	P	LABADIE2	3	1145.3	2014.2	33	2.925	10528.7	4348.5	IND	0.152	0.363	0.738	0.573	26.984	26.984	31.27	3.052	0.241	26.984	0
18010513	P	LABADIE5	3	17.9	52.6	32	2.777	9995.9	4310.6	DIR	0.157	0	0.738	0.578	0	0	0	0	0	0	0
19052610	P	LAB34	3	551	2254.2	25	4.318	15545.2	4312.9	PEN	0.059	0.906	0.664	0.492	54.166	54.166	57.323	4.055	0.148	54.166	0
19052610	P	LABADIE1	3	433	1075.1	25	4.862	17503.1	4371.5	IND	0.067	0.411	0.674	0.58	0.036	0.036	0.038	0.002	0.163	0.036	0
19052610	P	LABADIE2	3	507.3	2023.8	25	4.162	14982.5	4348.5	PEN	0.064	0.774	0.669	0.538	44.129	44.129	46.947	3.16	0.157	44.129	0
19052610	P	LABADIE5	3	19.1	51	33	3.996	14387.2	4310.6	DIR	0.069	0.001	0.674	0.593	0	0	0	0	0	0	0

Table C-8: Source and Plume Details for Top 10 Highest SO_2 Predicted Concentrations – Labadie Database North Site

YYMMDDHH	SOURCE TYPE	SOURCE ID	RCPT NO.	FINAL PLUME HT.	DIST. FINAL PL. HT.	WDIR FINAL HT.	EFFECT. WSPD	3600* UEFF	DISTANCE TO RCPT	PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT SIGMA_V	EFFECT. SIGMA_W	HOURLY CONC	AERVAL	COHERENT	PANCAKE	GAMFACT	PRMVAL	POT. TEMP. GRAD.
19020114	P	LAB34	4	722.7	852.4	188	1.483	5340.6	3854.2	PEN	0.176	1	0.407	0.19	51.968	51.968	61.739	6.121	0.37	51.968	0
19020114	P	LABADIE1	4	629.3	852.4	188	1.305	4699	3758.4	PEN	0.234	1	0.422	0.284	64.283	64.283	81.122	9.266	0.371	64.283	0
19020114	P	LABADIE2	4	646.8	852.4	188	1.387	4993.8	3796	PEN	0.209	1	0.419	0.266	61.637	61.637	75.78	8.159	0.371	61.637	0
19020114	P	LABADIE5	4	29.3	51.9	340	0.625	2250.8	3858.4	DIR	0.994	0.001	0.44	0.379	0	0	0	0	0	0	0
19020115	P	LAB34	4	702.4	956.7	189	0.663	2386.9	3854.2	PEN	0.736	1	0.402	0.222	67.144	67.144	165.026	32.1	PLUME OUT	OF WAKE	0
19020115	P	LABADIE1	4	623.5	956.7	189	0.743	2674.6	3758.4	PEN	0.693	0.938	0.405	0.253	52.256	52.256	119.019	22.643	0.073	52.256	0
19020115	P	LABADIE2	4	637.4	956.7	189	0.74	2664.8	3796	PEN	0.701	0.963	0.405	0.25	52.65	52.65	121.84	23.185	0.076	52.65	0
19020115	P	LABADIE5	2	26.3	51.9	354	0.928	3340.4	3346.3	DIR	0.415	0.001	0.41	0.296	0	0	0	0	0	0	0
18071912	P	LAB34	4	651.4	1433.3	193	2.787	10032.3	3854.2	PEN	0.169	0.902	0.768	0.589	67.012	67.012	78.91	8.433	0.371	67.012	0
18071912	P	LABADIE1	4	581.4	1433.3	193	2.71	9757.2	3758.4	PEN	0.179	0.73	0.789	0.647	43.002	43.002	51.204	5.357	0.369	43.002	0
18071912	P	LABADIE2	4	586.8	1433.3	193	2.711	9761	3796	PEN	0.178	0.747	0.788	0.644	42.353	42.353	50.391	5.305	0.37	42.353	0
18071912	P	LABADIE5	4	20.1	50.8	193	2.57	9251.1	3858.4	DIR	0.193	0.001	0.806	0.694	0	0	0	0	0	0	0
17051510	P	LAB34	4	701.2	1197.1	198	2.359	8494	3854.2	PEN	0.235	0.864	0.757	0.652	59.245	59.245	74.421	9.786	0.133	59.245	0
17051510	P	LABADIE1	4	639.6	1197.1	198	2.261	8139	3758.4	PEN	0.263	0.724	0.778	0.688	38.707	38.707	50.186	6.472	0.142	38.707	0
17051510	P	LABADIE2	4	643.5	1197.1	198	2.263	8145.2	3796	PEN	0.261	0.735	0.777	0.686	39.013	39.013	50.45	6.584	0.139	39.013	0
17051510	P	LABADIE5	4	23.1	50.8	171	1.874	6746.1	3858.4	DIR	0.352	0.001	0.805	0.744	0	0	0	0	0	0	0
17053010	P	LAB34	4	1035.4	834.2	212	0.753	2712.2	3854.2	PEN	0.516	0.72	0.356	0.514	61.059	61.059	98.403	26.095	PLUME OUT	OF WAKE	0
17053010	P	LABADIE1	4	931.5	834.2	212	0.755	2717.9	3758.4	PEN	0.551	0.534	0.369	0.542	31.525	31.525	53.722	13.41	PLUME OUT	OF WAKE	0
17053010	P	LABADIE2	4	934.2	834.2	212	0.755	2717.7	3796	PEN	0.55	0.54	0.369	0.542	32.259	32.259	54.698	13.908	PLUME OUT	OF WAKE	0
17053010	P	LABADIE5	1	44.8	51.1	243	0.783	2818.1	3723	DIR	0.501	0.001	0.381	0.552	0	0	0	0	0	0	0
17060410	P	LAB34	4	843.1	799.9	188	1.111	3999.3	3854.2	PEN	0.542	0.914	0.572	0.525	54.707	54.707	98.365	17.838	0.37	54.707	0
17060410	P	LABADIE1	4	757.2	799.9	188	1.107	3986.1	3758.4	PEN	0.58	0.777	0.585	0.564	30.883	30.883	58.645	10.784	0.371	30.883	0
17060410	P	LABADIE2	4	756.1	799.9	188	1.107	3986	3796	PEN	0.581	0.775	0.585	0.564	29.074	29.074	55.313	10.129	0.371	29.074	0
17060410	P	LABADIE5	1	33.9	50.9	255	1.063	3826.7	3723	DIR	0.675	0.001	0.611	0.613	0	0	0	0	0	0	0
19062711	P	LAB34	4	757.5	793.8	182	2.127	7656.5	3854.2	PEN	0.154	1	0.554	0.231	25.779	25.779	29.847	3.396	0.088	25.779	0
19062711	P	LABADIE1	4	626.6	793.8	182	2.023	7283.2	3758.4	PEN	0.205	1	0.585	0.414	43.703	43.703	53.23	6.84	0.085	43.703	0
19062711	P	LABADIE2	4	596.5	793.8	182	1.853	6669.6	3796	PEN	0.227	1	0.597	0.474	43.805	43.805	54.626	6.932	0.086	43.805	0
19062711	P	LABADIE5	1	55	50.6	228	0.49	1763.8	3723	IND	0.519	0.004	0.627	0.385	0	0	0	0	0	0	0
18060609	P	LAB34	3	706.4	336.4	68	0.532	1914.4	4312.9	PEN	1	1	0.6	0.098	40.85	40.85	65.308	40.85	PLUME OUT	OF WAKE	0
18060609	P	LABADIE1	2	598.5	336.4	68	0.542	1951.6	3203.1	PEN	1	1	0.612	0.207	36.971	36.971	7.96	36.971	PLUME OUT	OF WAKE	0
18060609	P	LABADIE2	2	605.7	336.4	68	0.539	1941.4	3259	PEN	1	1	0.611	0.195	36.188	36.188	6.502	36.188	PLUME OUT	OF WAKE	0
18060609	P	LABADIE5	2	31.1	50.9	39	0.689	2479.1	3346.3	DIR	1	0.002	0.652	0.488	0	0	0	0	0	0	0
19120713	P	LAB34	4	558.6	1010.4	174	1.978	7121.1	3854.2	PEN	0.199	1	0.588	0.438	64.803	64.803	77.339	14.189	PLUME OUT	OF WAKE	0
19120713	P	LABADIE1	4	486.8	1010.4	174	1.887	6792.4	3758.4	PEN	0.219	0.831	0.593	0.503	33.647	33.647	40.758	8.23	PLUME OUT	OF WAKE	0
19120713		LABADIE2 <--- Source is not emitting during this hour																			
19120713	P	LABADIE5	4	24.9	51.9	191	1.728	6221.3	3858.4	DIR	0.258	0.001	0.597	0.532	0	0	0	0	0	0	0
17043015	P	LAB34	4	684.6	619.8	171	0.726	2614.3	3854.2	PEN	0.814	1	0.46	0.29	39.844	39.844	105.471	24.83	PLUME OUT	OF WAKE	0
17043015	P	LABADIE1	4	614.2	619.8	171	0.784	2823.5	3758.4	PEN	0.827	1	0.46	0.344	29.003	29.003	77.842	18.775	PLUME OUT	OF WAKE	0
17043015	P	LABADIE2	4	625.3	619.8	171	0.783	2820.1	3796	PEN	0.826	1	0.46	0.34	32.713	32.713	88.479	21.003	PLUME OUT	OF WAKE	0
17043015	P	LABADIE5	4	33.4	51.1	166	0.907	3263.5	3858.4	DIR	0.893	0.002	0.46	0.425	0	0	0	0	0	0	0

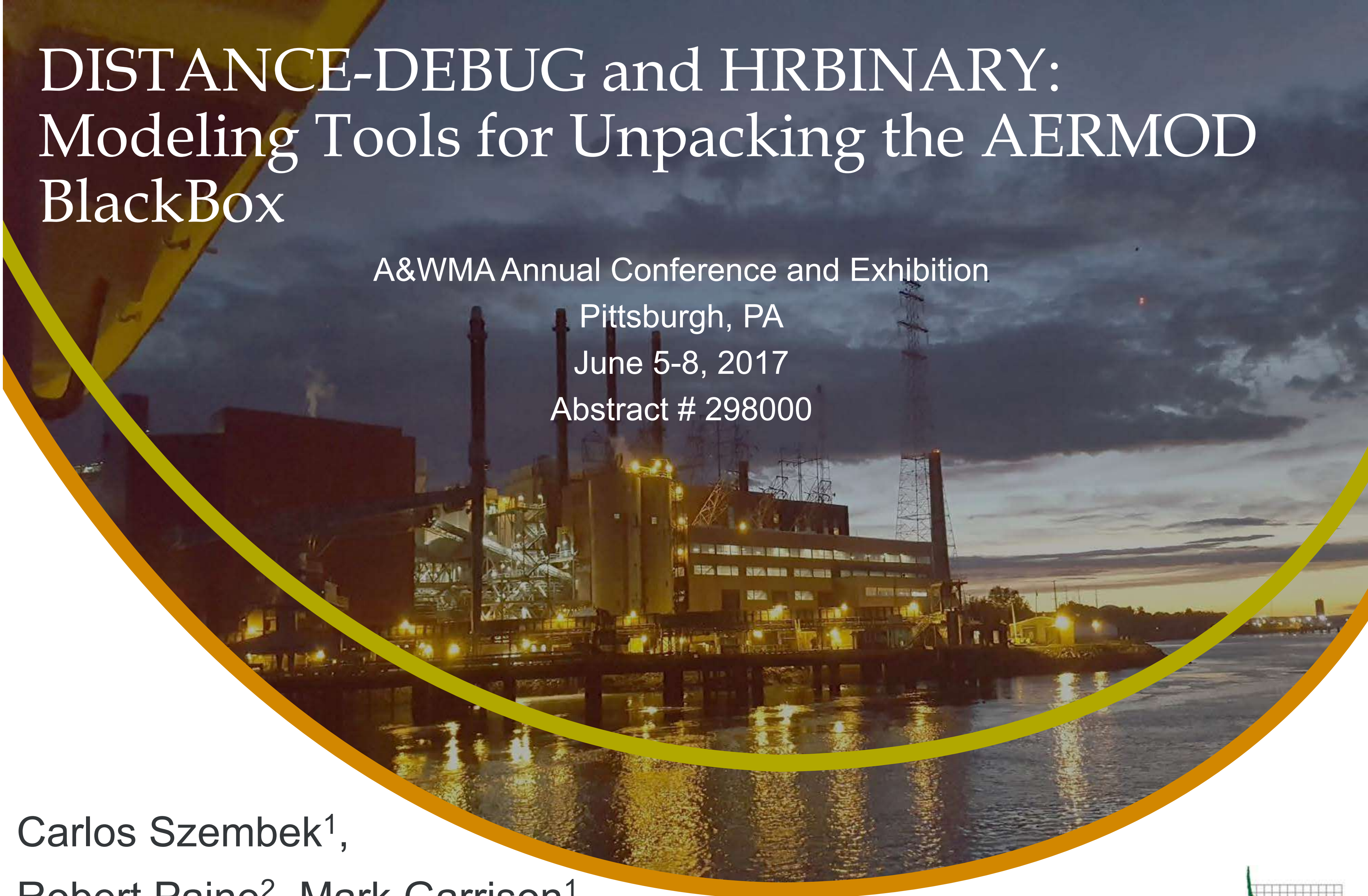
Figure B-1: Top 10 Concentrations vs. Hour of Day and Wind Speed – All 4 Labadie Monitoring Sites

This document included copyrighted material that has been removed. The following documents were removed and available to view at EPA Region 6 office.

Weil, J.C., Corio, L.A., and Brower, R.P., August 1997. A PDF Dispersion Model for Buoyant Plumes in the Convective Boundary Layer. Published in Journal of Applied Meteorology Volume 36.

Moore, G .E., Milich, L .B., Liu, M. K., 1988: Plume Behaviors Observed Using Lidar and SF_6 Tracer at a Flat and Hilly Site. Atmospheric Environment Vol. 22, No. 8, pp. 1673-1688

Weil, J.C., 2019 Prelimanary Draft V4 - New Dispersion Model for Highly-Buoyant Plumes in the Convective Boundary Layer. Prepared for Collie Airshed Study Consortium, Perth, AU. (Document was provided by AECOM and TCEQ with erroneous date of January 2, 2020. EPA Region 6 confirmed correct date from Dr. J.C. Weil and AECOM as January 2, 2019.



DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD BlackBox

A&WMA Annual Conference and Exhibition
Pittsburgh, PA
June 5-8, 2017
Abstract # 298000

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The business of sustainability

AECOM ERM

DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD BlackBox

AERMOD, the U.S. Environmental Protection Agency preferred air dispersion model, is a steady-state model that incorporates concepts of planetary boundary layer turbulence with plume dispersion dynamics. The model statistically approximates horizontal and vertical plume transport interacting with hourly meteorology, terrain and any identified impact from building downwash and urban enhanced buoyancy. An array of pre-processors generates meteorological, topographic and building downwash inputs for AERMOD. These inputs allow AERMOD to calculate hourly ground level concentration gradients.

Despite the quality of the inputs, assumptions or faulty implementation within a model's formulation can potentially generate questionable or even erroneous results. While there are several debugging options for investigating AERMOD's intermediary calculations, these current options produce massive cumbersome output files unless run on a single receptor or single hour. The Electric Power Research Institute (EPRI) sponsored a study to develop a model tool, "DISTANCE-DEBUG" that would efficiently diagnose causes for predicted high concentrations. DISTANCE-DEBUG generates a streamlined hourly file echoing key meteorology and tabulating AERMOD-calculated plume dynamics for each point, volume and area source. Hourly intermediary concentration calculations are also reported for the coherent plume. Example cases will be presented that highlight the DISTANCE-DEBUG features, particularly its legibility and ease of use.

A separate EPRI-funded tool, "HRBINARY", in conjunction with a concentration processor ("BINMERGE-2017") will be discussed that allows for binary output from multiple AERMOD runs to be post-processed, including an example case of two buoyant line sources using different buoyancy parameters, an option not currently available in AERMOD version 16216r.

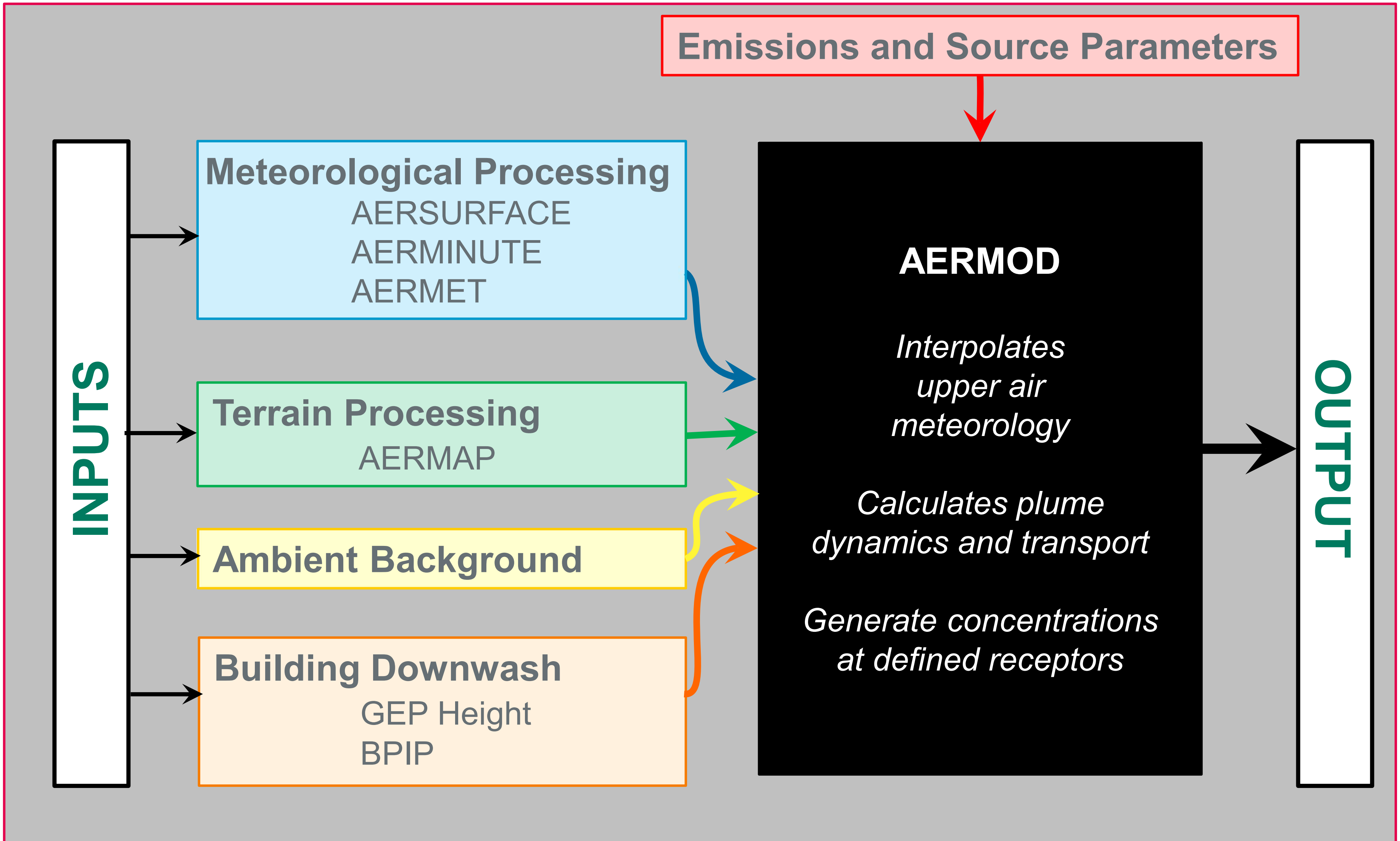
Overview

In 2012, the Electric Power Research Institute (EPRI) sponsored two modeling tools:

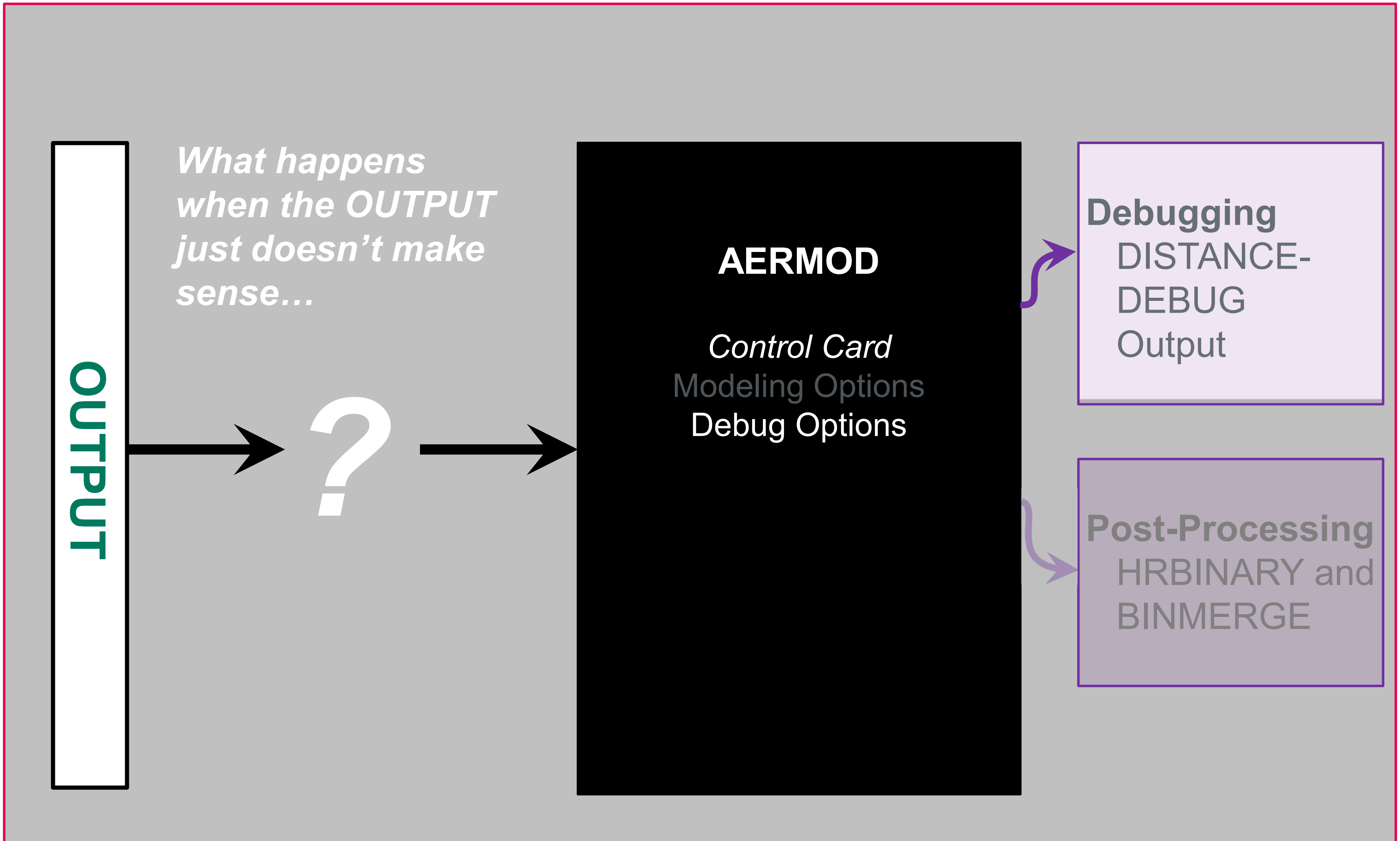
- **DISTANCE-DEBUG** an AERMOD debugging tool intended to streamline the diagnostics associated with predicted high concentrations.

- **HRBINARY,** a post-processing option in AERMOD that (in conjunction with another post-processor, "BINMERGE") allows for merged output from multiple (but separately performed) AERMOD runs to be analyzed to generate NAAQS-ranked design value output.

The AERMOD BlackBox



The AERMOD BlackBox



Debugging…so many options

- **MODEL:** General modeling debug file
- **METEOR:** General meteorological
- **PRIME:** PRIME downwash
- **DEPOS:** Deposition (for both gas & particle)
- **AREA or LINE:** Area, Line and Open Pit
- **PVMRM or OLM or ARM or ARM2:** NO_x-to-NO_2 conversion

So why the need for another debug file?

…can be overwhelming

Excerpt from 60,000 line PRIME Debug file

```
PRIME Module Results for Current Source and Hour
           (all lengths in meters)
 ------------------------------------------------

     XB       X       Z   Hwake    Hcav     Sz      Sy    Ufac  dUfac  R->Sz   dRdx  Pos   Szcav   Sycav

    48.5     0.0    42.7   74.9    49.6     0.0     0.0  0.639  0.000    0.0  0.000   1    14.2    34.5
    48.5     0.0    43.7   74.9    49.6     0.3     0.3  0.638  0.000    1.6  0.000   1    14.2    34.5
.
.
.
   970.2   921.8    47.0  182.7     0.0    66.8    86.9  0.832  0.001   47.2  0.038   3    65.1   109.4
  1008.2   959.8    46.6  185.0     0.0    67.8    88.3  0.835  0.001   47.2  0.003   3    66.2   111.1

 YR/MN/DY/HR:         10070101  ISRC:            1  IREC:             1

  GAMFACT =   6.940565230893733E-004
  AERVAL  =    5.69810811953800
  PRMVAL  =    121.518405396800
  HRVAL   =    5.77849395236943

 YR/MN/DY/HR:          10070101

 WAKE_SCALES inputs:
    HB    =    49.6200000000000       (m)
    WB    =    86.5100000000000       (m)
    LB    =    112.940000000000       (m)

 WAKE_SCALES output:
    Scale length (R)               =    59.7209366698920
    Max. cavity height (HR)        =    62.7586060673762
    Length of downwind cavity (LR) =    85.7776606883091
    Length of roof cavity (LC)     =    53.7488430029028
 PRIME Effective Parameters:
 ZLO, ZHI     =   0.500000000000000        178.035578770569
 SWEFF, SVEFF =   0.168846389190163       0.343228206052833
 UEFF,  TGEFF =    6.86456412105667       5.997118404810090E-002
```

…can be overwhelming (cont'd.)

Excerpt from 60,000 line PRIME Debug file

NNP	X	Y	Z	R	U	V	W	USC	PHI	DEN	TP	UA	RA	TA	DUDZ	DPDZ	DZDS	DYDS	IPOS	DELTAZ
1	0.08	0.00	47.62	2.61	1.78	0.00	9.65	9.82	1.3887	1.090	312.02	5.57	1.180	288.37	0.057	0.070	0.000	0.000	1	0.994
2	0.35	0.00	48.58	3.47	2.84	0.00	7.02	7.58	1.1862	1.114	305.41	5.63	1.179	288.42	0.056	0.070	0.000	0.000	1	1.953
3	0.80	0.00	49.47	4.27	3.50	0.00	5.42	6.45	0.9974	1.129	301.38	5.67	1.179	288.48	0.056	0.069	0.000	0.000	1	2.839
4	1.40	0.00	50.27	4.97	3.93	0.00	4.41	5.91	0.8423	1.138	298.83	5.73	1.179	288.53	0.102	0.069	0.000	0.000	3	3.635
5	2.11	0.00	51.36	5.54	4.25	0.00	3.73	5.66	0.7212	1.144	297.15	5.81	1.178	288.59	0.103	0.069	0.387	0.000	3	4.730
6	2.88	0.00	52.39	6.01	4.48	0.00	3.27	5.54	0.6300	1.149	295.99	5.89	1.178	288.65	0.105	0.069	0.399	0.000	3	5.759
7	3.71	0.00	53.35	6.41	4.66	0.00	2.93	5.50	0.5609	1.152	295.16	5.96	1.178	288.71	0.106	0.069	0.393	0.000	3	6.716
8	4.57	0.00	54.23	6.76	4.80	0.00	2.67	5.49	0.5074	1.154	294.53	6.02	1.177	288.76	0.107	0.069	0.376	0.000	3	7.604
9	5.45	0.00	55.06	7.07	4.91	0.00	2.46	5.50	0.4649	1.156	294.03	6.08	1.177	288.81	0.109	0.069	0.354	0.000	3	8.429
10	6.35	0.00	55.83	7.35	5.01	0.00	2.30	5.51	0.4304	1.157	293.64	6.13	1.177	288.85	0.110	0.069	0.331	0.000	3	9.196
11	7.26	0.00	56.54	7.61	5.09	0.00	2.16	5.53	0.4016	1.159	293.31	6.17	1.176	288.90	0.111	0.069	0.307	0.000	3	9.910
12	8.19	0.00	57.21	7.86	5.16	0.00	2.04	5.55	0.3773	1.160	293.03	6.21	1.176	288.94	0.113	0.069	0.283	0.000	3	10.575
13	9.12	0.00	57.83	8.10	5.21	0.00	1.94	5.56	0.3565	1.160	292.79	6.24	1.176	288.97	0.114	0.069	0.260	0.000	3	11.196
14	10.06	0.00	58.41	8.32	5.27	0.00	1.85	5.58	0.3385	1.161	292.58	6.27	1.176	289.01	0.115	0.069	0.237	0.000	3	11.776

```
NUMRISE call to WAKE_DFSN
x,y,z,z+zcum:     10.05785       0.00000      55.07828      58.40623
ds,u,w      :      1.00000       5.26501       1.85351
xb,phi      :     18.14785       0.33849
szi,syi     :      2.42068       2.46556

WAKE_XA Calculations:
ambiz,  ambiy  =   2.459681142350115E-002  5.000000000000001E-002
farizt, fariyt =   3.197585485055150E-002  6.500000000000002E-002
xaz,    xay    =    1008.75405004838        1008.75405004838

----- WAKE_DFSN:        NWAK =           50
Z-dispersion reaches ambient at:    1000.66405004838
Y-dispersion reaches ambient at:    1000.66405004838
xadj, yadj, xi  (m) =         -8.09000        -3.10000        18.14785
xbc, distc, xdc (m) =        112.94000       104.85000       198.71766
lwak,  nws,  npw    =  T          0          497
lcav,  ncs,  npc    =  T         48
```


AECOM ERM

DISTANCE-DEBUG: Focus on Clarity

```
* * * * * * * AERMOD DISTANCE DEBUG FILE * * * * * * *

PLUME TYPES:
  GAUSSIAN:    Idealized plume under stable conditions or when the stack height > the mixing
               height under unstable conditions
  DIRECT:      Direct transport of plume material to the ground within the mixed layer
  INDIRECT:    Portion of the plume caught in convective updrafts but does not penetrate elevated
               inversions. The indirect plume material eventually is reflected down to the ground.
  PENETRATED:  Portion of the plume that penetrates the elevated inversion and is eventually
               re-entrained into the CBL (Convective Boundary Layer)

OTHER TERMS USED:
  MEAND FRAC:  Meander fraction (m.f.); the fraction of the total concentration component associated with
               the meander component. The remaining fraction is assigned to the coherent component.
  PART PEN FRAC: Partial penetration fraction
  HRVAL:       Overall calculated hourly concentration; HRVAL = (1-GAMFACT)*AERVAL + (GAMFACT*PRMVAL)
                                    where AERVAL = m.f.*PANCAKE + (1 - m.f.)*COHERENT
                             For volume sources: HRVAL = (1-m.f.)*AERVAL + (m.f.)*PANCAKE
                             For area sources:   HRVAL = AbsoluteValue(VAL)*QTK*EMIFAC
  AERVAL:      Portion of hourly concentration not associated with downwash
  PRMVAL:      Portion of hourly concentration associated with downwash
  GAMFACT:     Gamma Factor; scaling factor associated with the PRMVAL
  PANCAKE:     Value from calculating a *pancak-ing* plume
  COHERENT:    The coherent portion of the plume NOT associated with downwash
  VAL:         Iterated integral hourly concentration for an area source
  QTK:         Adjusted emission rate factor
  EMIFAC:      Emission rate unit factor

*****************************************************************************************************
NOTES:     [1] The urban Monin-Obukhov length, URB_OBULEN, and the urban mechanical mixing height, ZI_URB,
               are displayed for only the first urban source group.
           [2] GAMFACT & PRMVAL marked with:
               PLUME OUT OF WAKE designates no downwash due to the plume being outside the wake zone
               RCPTR OUT OF WAKE designates no downwash affect at the maximum receptor
           [3] Hourly values and receptor numbers listed are for the MAXIMUM CONCENTRATION calculated
               for each source.
           [4] The potential temperature gradient listed is at the stack height.
           [5] Final plume height, effective windspeed (ueff), and the effective sigma v and w values
               are provided for only the COHERENT portion of the plume.
               The values associated with the MEANDER component are not listed.
           [6] A less-than sign, <, is inserted at column 62 for events when ueff would not transport
               the plume for a given source in one hour to the distance of the maximum receptor.
```

DISTANCE-DEBUG:

Each file begins with a legend of the extracted parameters

Some parameters are only reported for the **coherent plume** (versus the meander component of the plume)

DISTANCE-DEBUG Output

Basic met hourly met data

```
OBSERVED MET CONDITIONS FOR:  USTAR   WSTAR  OBULEN  URB_OBULEN  ZIMECH  ZICONV   ZI_URB    SFCZ0   THSTAR
YYMMDDHH: 12040102            (m/s)   (m/s)   (m)      (m)        (m)     (m)      (m)       (m)     (K)
                               0.13   -9.00   12.90        N.A.  103.00 -999.00    N.A.    0.4280   0.090
-------------------------------------------------------------------------------------------------------------
```

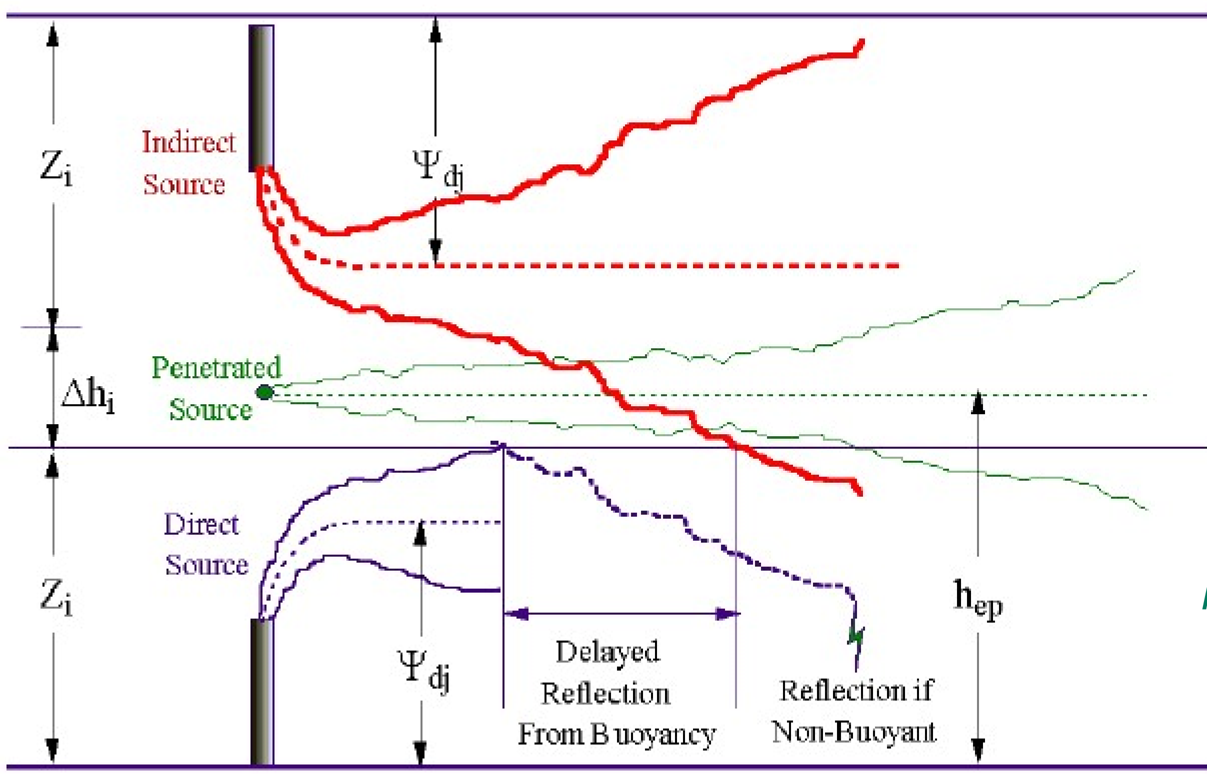
Followed by point source data

```
POINT SOURCES:
   SOURCE         RCPT   FINAL  DIST.  WDIR  Effect. <------ DISTANCE -----> MEAND.  PART.   EFFECT. EFFECT.   HOURLY                                                                POT.
   ID             NO.    PLUME  FINAL  FINAL WSPD    3600*       TO    PLUME FRAC.   PEN.    SIGMA_V SIGMA_W   CONC.       AERVAL    COHERENT    PANCAKE   GAMFACT     PRMVAL    TEMP.
                         HT.    PL.HT  HT.           ueff      RECEPT  TYPE          FRAC.                                                                                       GRAD.
                         (m)    (m)    (deg)  (m/s)  (m/s)      (m)                          (m/s)   (m/s)     (µg/m3)     (µg/m3)   (µg/m3)     (µg/m3)               (µg/m3)   (K/m)
------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
P MERGE001         329  153.1   269.4  273.    2.669   9610.1   3242.0 GAU   0.025   0.000   0.200   0.052     35.017      0.000      0.000      0.000  PLUME OUT OF WAKE  0.01637
  MERGEN01     <--- Source is not emitting during this hour
P POINT002        1130   31.5   172.3  273.    1.347   4848.7 < 9157.9 GAU   0.090   0.000   0.200   0.074      2.209      2.209      2.422      0.066  PLUME OUT OF WAKE  0.01637
P POINT003         329   14.4   158.4  273.    1.347   4848.7   3202.3 GAU   0.073   0.000   0.200   0.074     13.187     13.019     14.021      0.330   1.000     13.187  0.01278
P POINT004        1099   30.6   172.3  273.    1.347   4848.7 < 8260.8 GAU   0.085   0.000   0.200   0.074      2.880      2.880      3.141      0.055   0.000      6.682  0.01278
P POINT005         325   16.2   158.4  273.    1.347   4848.7   2779.5 GAU   0.070   0.000   0.200   0.074     15.001     15.001     16.095      0.397   0.000     39.017  0.01278
P POINT006         332   14.6   158.4  273.    1.347   4848.7   3637.3 GAU   0.077   0.000   0.200   0.074     14.365     14.365     15.528      0.358   0.000     24.576  0.01278
P POINT007         333   15.6   158.4  273.    1.347   4848.7   3690.4 GAU   0.077   0.000   0.200   0.074     14.284     14.284     15.448      0.354   0.000     23.986  0.00781
```

For each source DISTANCE-DEBUG marks predicted max impacts too distant to be reached by the effective wind speed

```
VOLUME AND AREA SOURCES:
   SOURCE         RCPT   FINAL  DIST.  WDIR  Effect. <------ DISTANCE
   ID             NO.    PLUME  FINAL  FINAL WSPD    3600*
                         HT.    PL.HT  HT.           ueff      RECEPT  TYPE                                 VAL                QTK    EMIFAC
                         (m)    (m)    (deg)  (m/s)  (m/s)                                                           (µg/m3)
----------------------------------------------------------------------------------------------------------------------------------------
  VOLUME01     <--- Source is not emitting during this hour
V VOLUME02        1105   45.0     0.0  273.    2.669   9610.1 <14473.7 DIR   0.083   0.200   0.052     0.002      0.002      0.000  N.A.    N.A.
  VOLUME03     <--- Source is not emitting during this hour
V VOLUME04        1105   45.0     0.0  273.    2.669   9610.1 <14255.1 DIR   0.082   0.200   0.052     0.002      0.002      0.000  N.A.    N.A.
  VOLUME05     <--- Source is not emitting during this hour
V VOLUME06         328    5.0     0.0  273.    0.929   3344.9   3055.8 DIR   0.222   0.200   0.079     0.507      0.648      0.017  N.A.    N.A.
  VOLUME07     <--- Source is not emitting during this hour
V VOLUME08        1090   35.0     0.0  273.    2.539   9141.4 <14347.0 DIR   0.114   0.200   0.054     0.025      0.029      0.001  N.A.    N.A.
  VOLUME09     <--- Source is not emitting during this hour
V VOLUME10         324    5.0     0.0  273.    0.929   3344.9   2681.8 DIR   0.217   0.200   0.079     0.634      0.804      0.021  N.A.    N.A.
A AREA01           325   10.0     0.0  273.    1.347   4848.7   3427.0 DIR   N.A.    0.200   0.074   236.915  0.237E+00       N.A.  0.1E-02 0.1E+07
```

Example of Reported Point Source Parameters



← Mixing Height, z_i

z_{conv}, z_{mech} or z_{urb}

Final plume height (centerline)

$\psi_{dj} = H_s + H_p$

Not shown:
Gaussian plume: idealized plume under stable conditions or during unstable conditions when stack height > mixing height

AECOM ERM

DISTANCE-DEBUG Output

OBSERVED MET CONDITIONS FOR:	USTAR (m/s)	WSTAR (m/s)	OBULEN (m)	URB_OBULEN (m)	ZIMECH (m)	ZICONV (m)	ZI_URB (m)	SFCZ0 (m)	THSTAR (K)
YYMMDDHH: 12040102	0.13	-9.00	12.90	N.A.	103.00	-999.00	N.A.	0.4280	0.090

POINT SOURCES:

SOURCE ID	RCPT NO.	FINAL PLUME HT. (m)	DIST. FINAL PL.HT (m)	WDIR FINAL HT. (deg)	Effect. WSPD (m/s)	<------ DISTANCE 3600* ueff (m/s)		TO RECEPT (m)	-----> PLUME TYPE	MEAND. FRAC.	PART. PEN. FRAC.	EFFECT. SIGMA_V (m/s)	EFFECT. SIGMA_W (m/s)	HOURLY CONC. (µg/m3)	AERVAL (µg/m3)	COHERENT (µg/m3)	PANCAKE (µg/m3)	GAMFACT	PRMVAL (µg/m3)	POT. TEMP. GRAD. (K/m)
P MERGE001	329	153.1	269.4	273.	2.669	9610.1		3242.0	GAU	0.025	0.000	0.200	0.052	35.017	0.000	0.000	0.000	PLUME OUT OF WAKE		0.01637
MERGEN01	<--- Source is not emitting during this hour																			
P POINT002	1130	31.5	172.3	273.	1.347	4848.7	<	9157.9	GAU	0.090	0.000	0.200	0.074	2.209	2.209	2.422	0.066	PLUME OUT OF WAKE		0.01637
P POINT003	329	14.4	158.4	273.	1.347	4848.7		3202.3	GAU	0.073	0.000	0.200	0.074	13.187	13.019	14.021	0.330	1.000	13.187	0.01278
P POINT004	1099	30.6	172.3	273.	1.347	4848.7	<	8260.8	GAU	0.085	0.000	0.200	0.074	2.880	2.880	3.141	0.055	0.000	6.682	0.01278
P POINT005	325	16.2	158.4	273.	1.347	4848.7		2779.5	GAU	0.070	0.000	0.200	0.074	15.001	15.001	16.095	0.397	0.000	39.017	0.01278
P POINT006	332	14.6	158.4	273.	1.347	4848.7		3637.3	GAU	0.077	0.000	0.200	0.074	14.365	14.365	15.528	0.358	0.000	24.576	0.01278
P POINT007	333	15.6	158.4	273.	1.347	4848.7		3690.4	GAU	0.077	0.000	0.200	0.074	14.284	14.284	15.448	0.354	0.000	23.986	0.00781

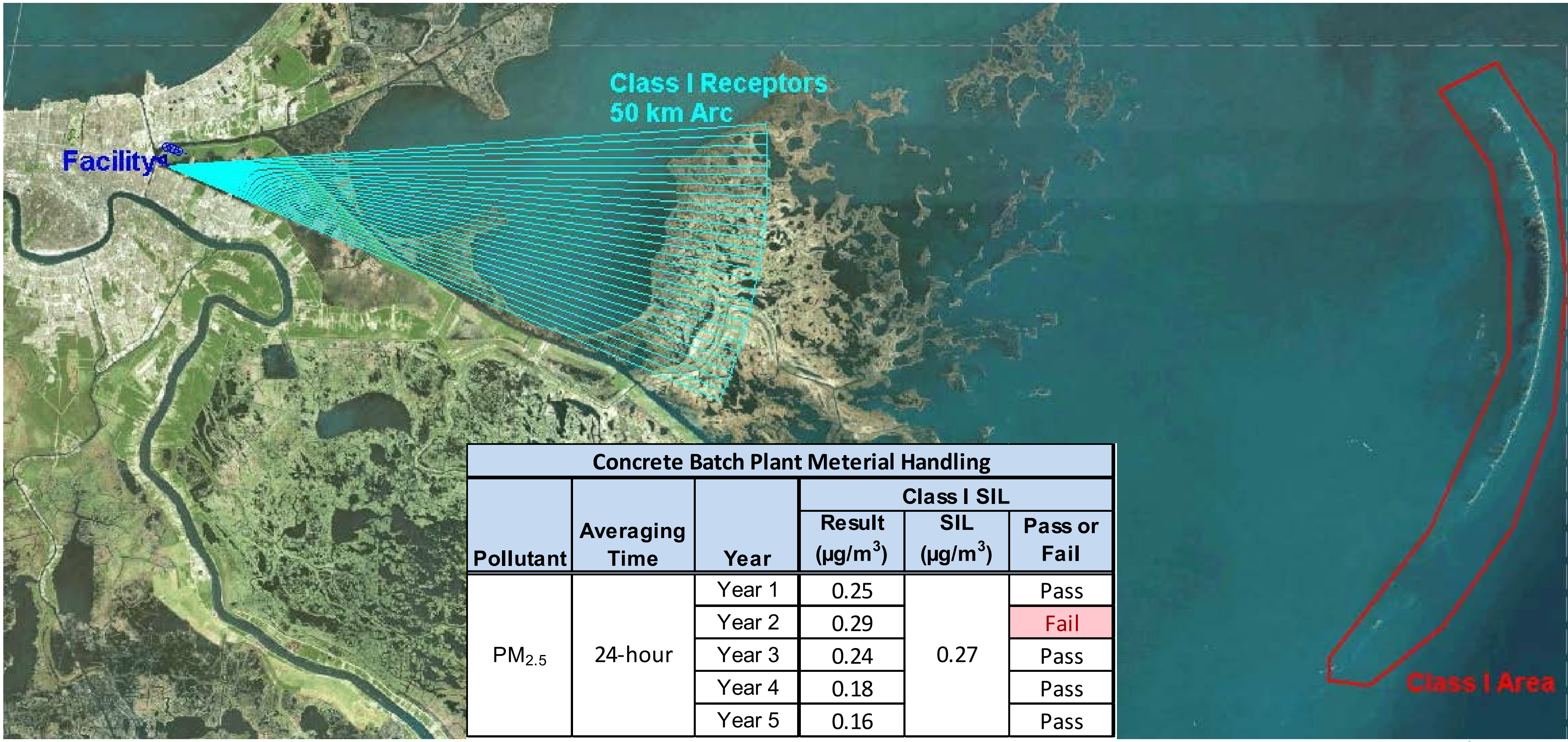
VOLUME AND AREA SOURCES:

SOURCE ID	RCPT NO.	FINAL PLUME HT. (m)	DIST. FINAL PL.HT (m)	WDIR FINAL HT. (deg)	Effect. WSPD (m/s)	<------ DISTANCE 3600* ueff (m/s)		TO RECEPT (m)	-----> PLUME TYPE	MEAND. FRAC.	EFFECT. SIGMA_V (m/s)	EFFECT. SIGMA_W (m/s)	HOURLY CONC. (µg/m3)	AERVAL or VAL (µg/m3)	PANCAKE (µg/m3)	QTK	EMIFAC
VOLUME01	<--- Source is not emitting during this hour																
V VOLUME02	1105	45.0	0.0	273.	2.669	9610.1	<	14473.7	DIR	0.083	0.200	0.052	0.002	0.002	0.000	N.A.	N.A.
VOLUME03	<--- Source is not emitting during this hour																
V VOLUME04	1105	45.0	0.0	273.	2.669	9610.1	<	14255.1	DIR	0.082	0.200	0.052	0.002	0.002	0.000	N.A.	N.A.
VOLUME05	<--- Source is not emitting during this hour																
V VOLUME06	328	5.0	0.0	273.	0.929	3344.9		3055.8	DIR	0.222	0.200	0.079	0.507	0.648	0.017	N.A.	N.A.
VOLUME07	<--- Source is not emitting during this hour																
V VOLUME08	1090	35.0	0.0	273.	2.539	9141.4	<	14347.0	DIR	0.114	0.200	0.054	0.025	0.029	0.001	N.A.	N.A.
VOLUME09	<--- Source is not emitting during this hour																
V VOLUME10	324	5.0	0.0	273.	0.929	3344.9		2681.8	DIR	0.217	0.200	0.079	0.634	0.804	0.021	N.A.	N.A.
A AREA01	325	10.0	0.0	273.	1.347	4848.7		3427.0	DIR	N.A.	0.200	0.074	236.915	0.237E+00	N.A.	0.1E-02	0.1E+07

DISTANCE-DEBUG assisted in the discovery of the AREACIRC issue associated with version16216

DISTANCE-DEBUG: Low-wind case

A case involving AERMOD 24-hour $PM_{2.5}$ modeling for the Class I PSD Increment SIL of 2 material handling transfer points at a concrete batch plant



Concrete Batch Plant Meterial Handling					
			Class I SIL		
Pollutant	Averaging Time	Year	Result (µg/m^3)	SIL (µg/m^3)	Pass or Fail
$PM_{2.5}$	24-hour	Year 1	0.25	0.27	Pass
		Year 2	0.29		Fail
		Year 3	0.24		Pass
		Year 4	0.18		Pass
		Year 5	0.16		Pass

DISTANCE-DEBUG: Low-wind Case

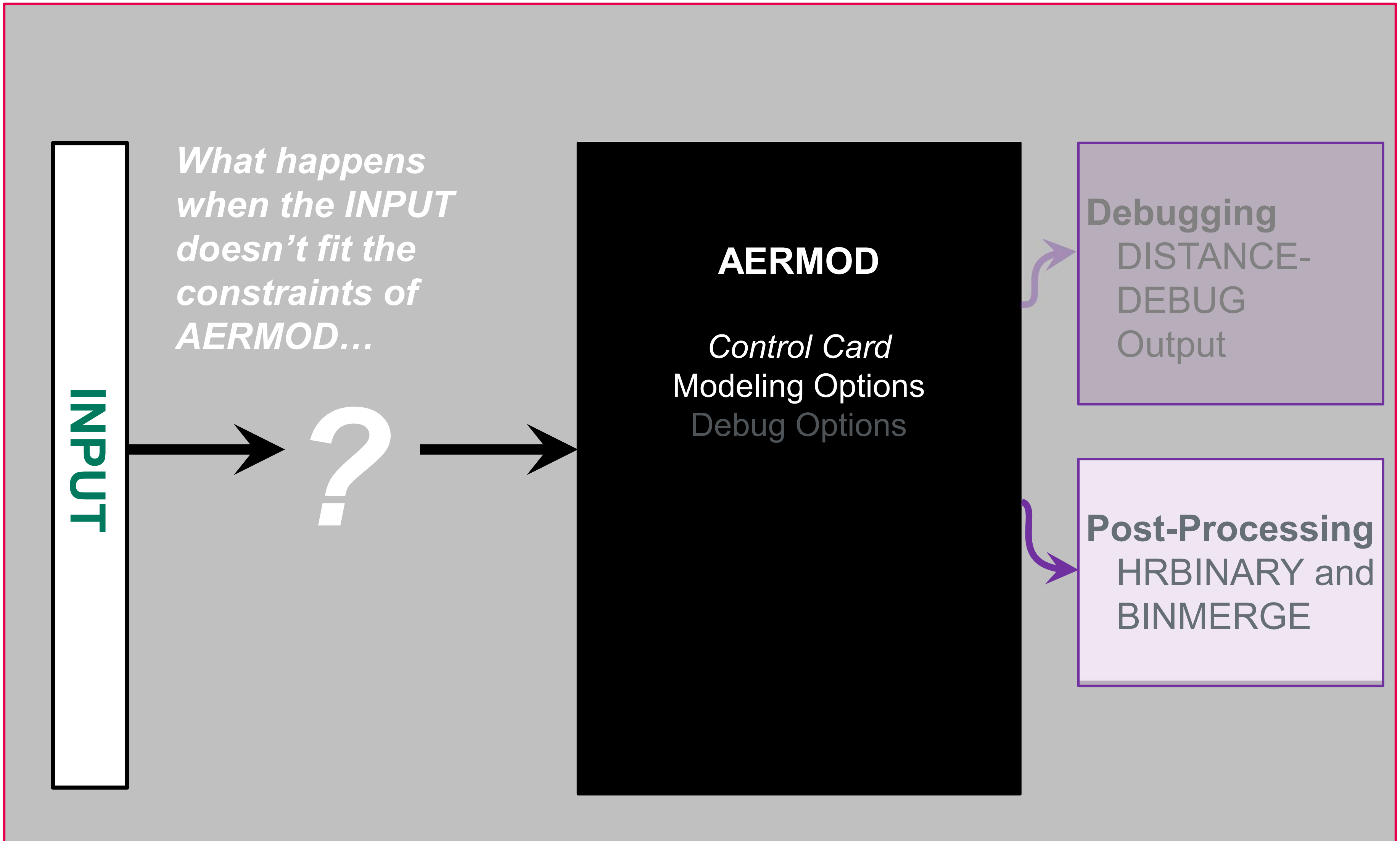
Point Sources	Q_s (g/s)	H_s (m)	T_s (K)	V_s (m/s)	D_s (m)
Turbine 1	1.0	30.0	810.0	37.0	4.5
Turbine 2	1.0	30.0	810.0	37.0	4.5
Volume Sources	Q_s (g/s)	H_s (m)	σ_y (m)	σ_z (m)	
Conveyor Loading	0.4	2	1.2	0.5	
Conveyor Unloading	0.4	2	1.2	0.5	

Hour	Source	u* (m/s)	u_{eff} (m/s)	1-hour Transit Distance (m)	Conc µg/m^3
4	Turb1	0.04	1.4	4,888	0.001
	Turb2		1.4	4,888	0.001
	Load		0.5	1,795	0.591
	Unload		0.5	1,795	0.644
5	Turb1	0.02	0.7	2,412	0.001
	Turb2		0.7	2,412	0.001
	Load		0.5	1,767	1.426
	Unload		0.5	1,767	1.631
6	Turb1	0.07	0.8	2,924	0.062
	Turb2		0.8	2,924	0.062
	Load		0.7	2,634	1.692
	Unload		0.7	2,634	1.816

Case run using default meteorology

3 low wind speed hours result in questionably high impacts 50 km out (from two gravel drop points)

The AERMOD BlackBox



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HRBINARY Post-processor

- "HRBINARY" allows for the import of an AERMOD unformatted 1-hour binary file to be added to any modeling run in order to perform the averaging of ranked highs for all currently evaluated averaging periods.

- Hence HRBINARY can allow output from multiple AERMOD runs of different sources to be merged, on an hour-by-hour, receptor-by-receptor basis

- When would this be necessary?

AECOM ERM

HRBINARY Example Case

- A steel mill with both stack and fugitive emission releases. Fugitive releases are represented by volume sources, area sources, and buoyant line sources (BLP). The BLP algorithms have been incorporated into AERMOD Version 16216r.
- The Plant operates 3 buoyant line sources.
- However, AERMOD v16216r allows only one set of average BLP parameters to be entered per run, these include the thermal buoyancy for line source and the associated downwash.

- Step 1:

  BINMERGE sums the separate AERMOD binary files for each different source groups. Each was modeled on the exact same grid.
- Step 2:

  AERMOD is re-run using the HRBINARY option. HRBINARY option takes the single merged binary file (from BINMERGE) and performs the pollutant and averaging time specific statistical ranking and averaging normally performed by AERMOD.

- Hence through this two-step method, very different sets of BLP source parameters can be more accurately represented in the modeling.

Further work

DISTANCE-DEBUG

- Does not currently support LINE, FLARE, BUOYLINE or OPENPIT sources
- Issue with reporting downwash contributions for impacts dominated by the “penetrated” plume type
- Provide an option for spreadsheet ready output

HRBINARY

- Allow for the acceptance of multiple binary files (thus eliminating the need for BINMERGE)
- For exploratory purposes, add an option to linearly scale concentrations in binary files for a weighted analysis between the binary files

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Review of models for dispersion of tall stack plumes at Collie: AERMOD questions

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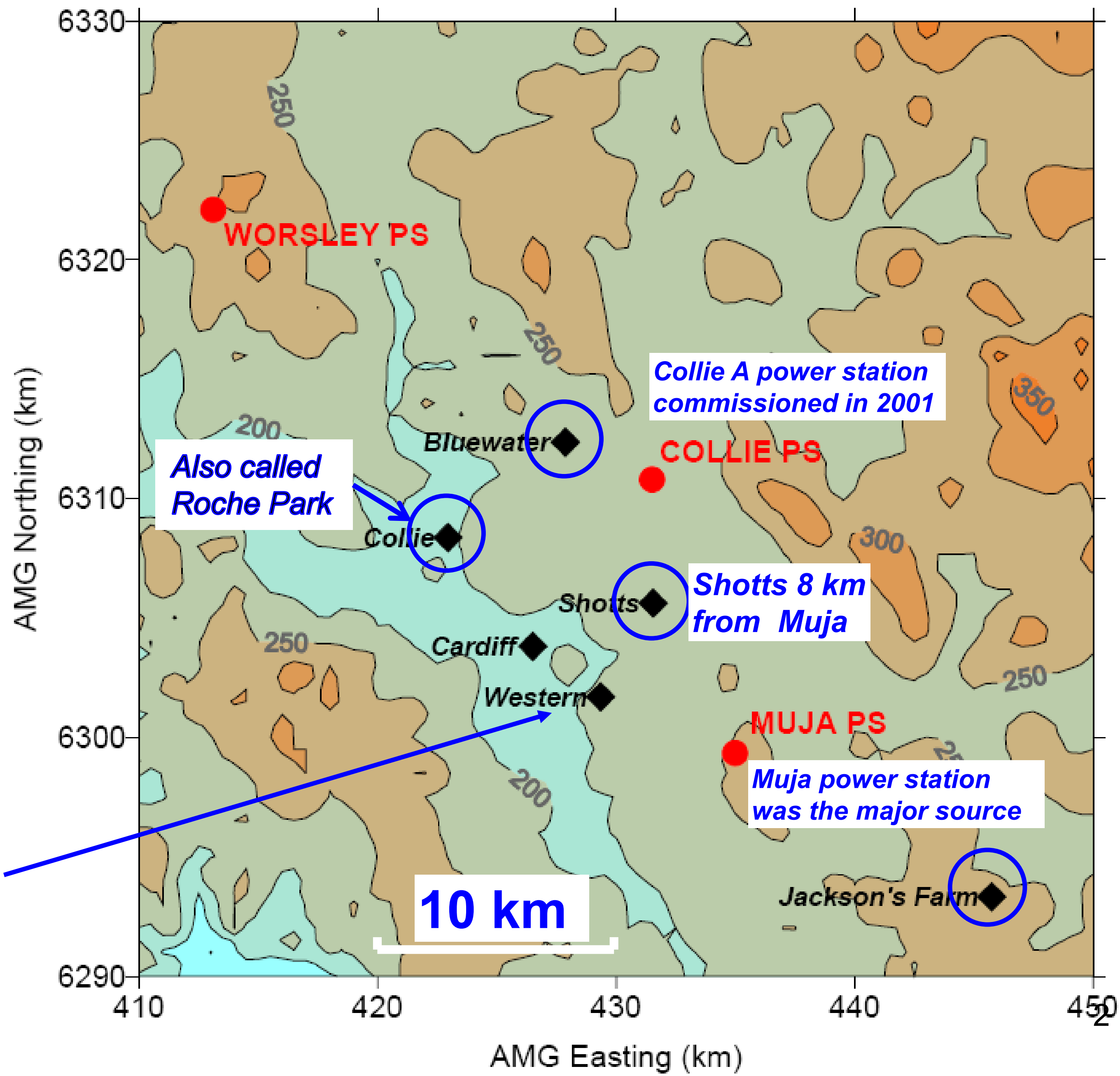
Western Australia
2013

Western Power monitoring program 1996 - 2001

SO_2 monitoring
Western Power
1998, 2001

Western 2 (W2) meteorological station



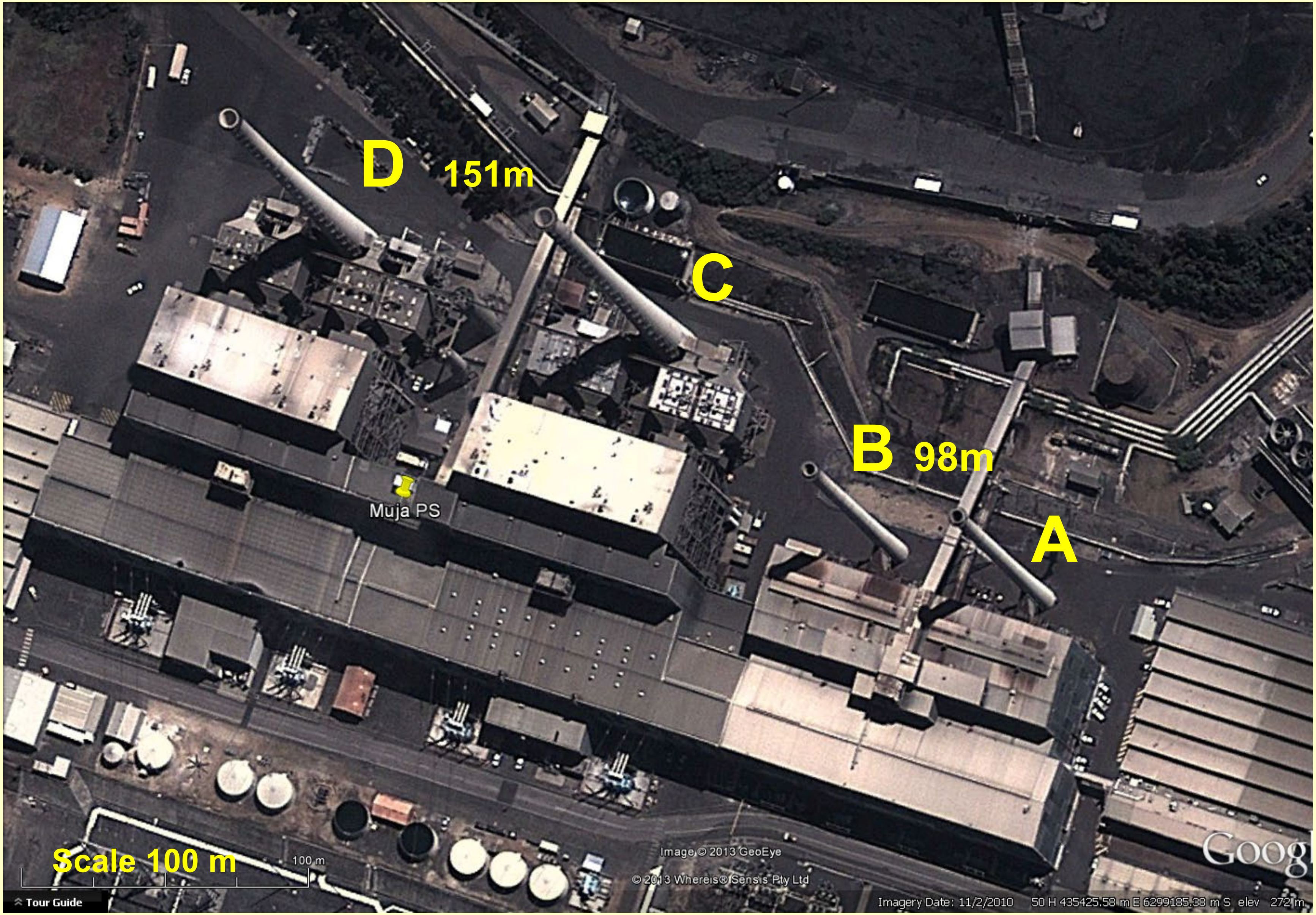
Emissions parameters (indicative)

In 1998, the year used for modelling below, only Muja and Worsley power stations were operating

Table 1 Emission parameters for existing and proposed sources as modelled by Environ (2007) based on estimates by SKM (2005).

Source (stack)	Stack Height (m)	Stack tip diameter (m)	Exit temp. (deg C)	Exit velocity (m s^{-1})	SO_2 (g s^{-1})	Power out
Muja A	98	3.94	200	19.0	269	120 MW
Muja B	98	3.94	200	19.0	269	120 MW
Muja C	151	5.91	133	20.4	779	400 MW
Muja D	151	5.91	133	19.0	779	400 MW
Collie A	170	5.23	152	24.4	515	300 MW
Worsley PS	76	4.00	130	23.7	315	
Worsley boiler xtn	105	2.50	130	24.5	71	
Bluewaters I	100	4.00	131	25.5	230	200 MW
Bluewaters II	100	4.00	131	25.5	230	200 MW

Muja Power Station



Inputs for AERMET/AERMOD – limitations of historical data (1998, 2001)

- No radiosondes near Collie.
  - Temperature profiles from TAPM were used;
  - AERMET also run with radiosonde data from Perth Airport, 160 km NNW, to test sensitivity.

- The only nearby cloud observations were from Donnybrook, 40 km SW of Collie on the coastal plain (possibly unrepresentative since Collie is at 200 m altitude, east of the Darling Escarpment). These observations were only twice daily (9 am, 3 pm). TAPM-generated cloud estimates (questionable quality) were tested.

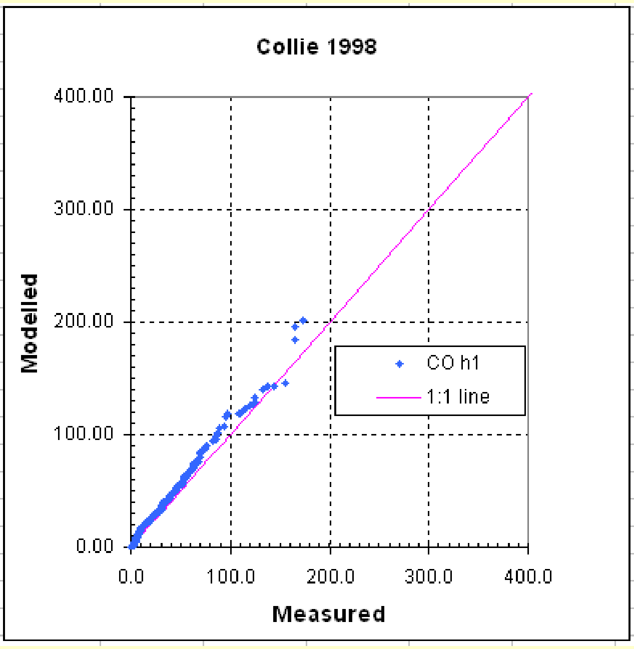
- AERMOD results (QQ plots) did not show much sensitivity to the different data options described above.

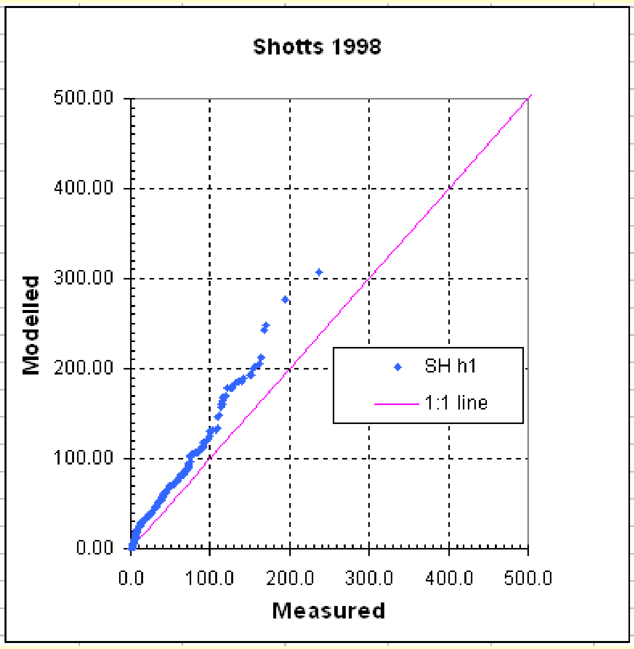
- Modelling described in these notes will be limited to 1998. Emissions from Muja power station were dominant. Emissions from the power station at the Worsley alumina refinery were relatively small and remote.

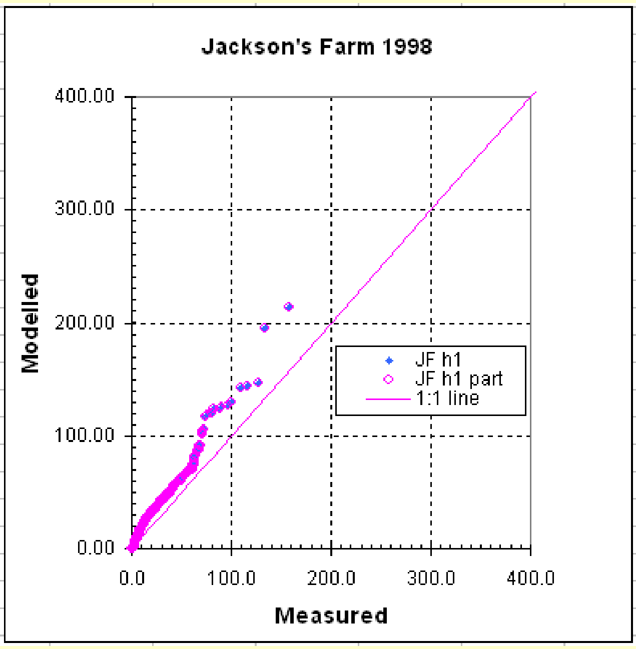
AERMOD run h1 (1998)

- measured met from W2 36m over forest, calculated solar radiation
- cloud from D'brook, temp profile (2 per day) from TAPM v403
- albedo = 0.1, Bowen = 1.0, z_0 = 1.0m

All Q-Q plots are for individual monitoring stations, i.e. predictions and observations paired in space but not time. Linear scales are used to better display the important higher concentrations.

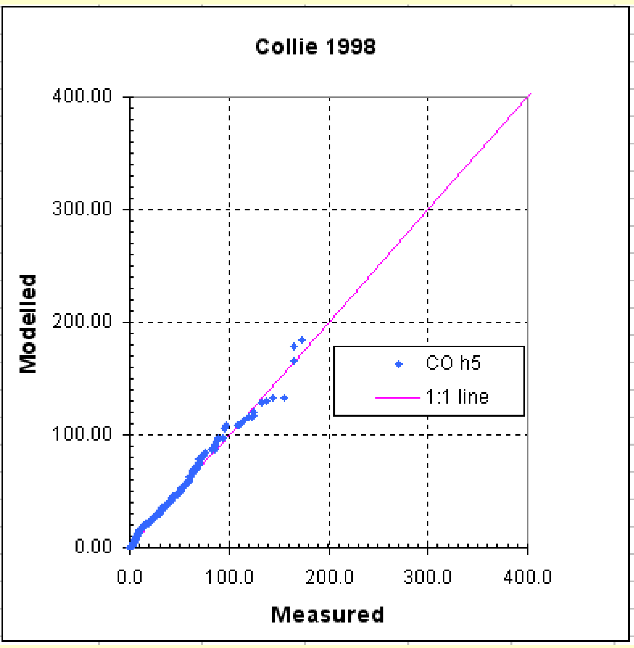


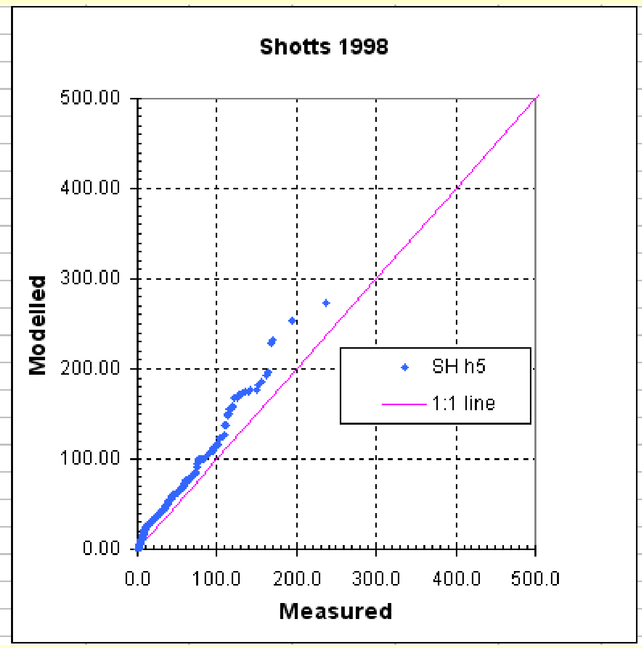


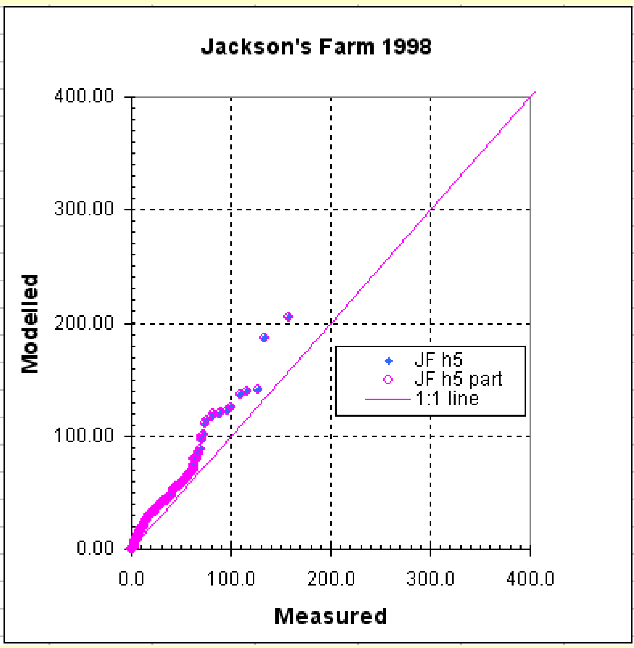


AERMOD h5

- as per h1 but topography modelled (Lakes software): concentrations reduced a little – probably due to Muja elevation.



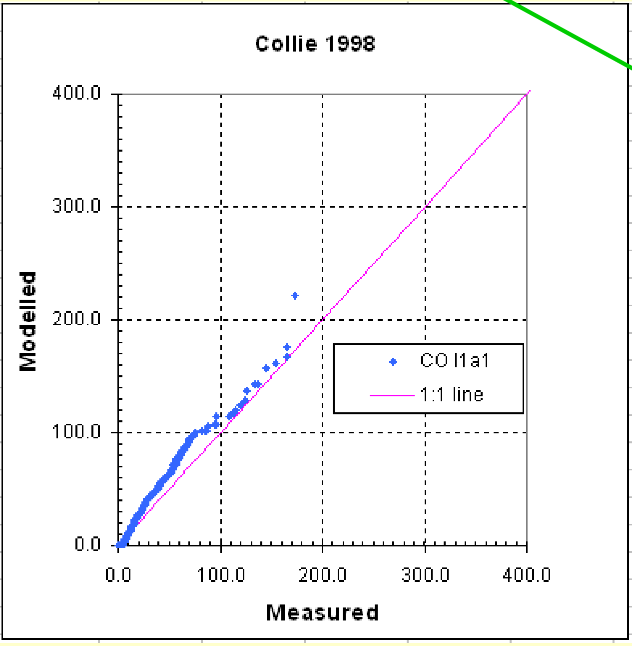


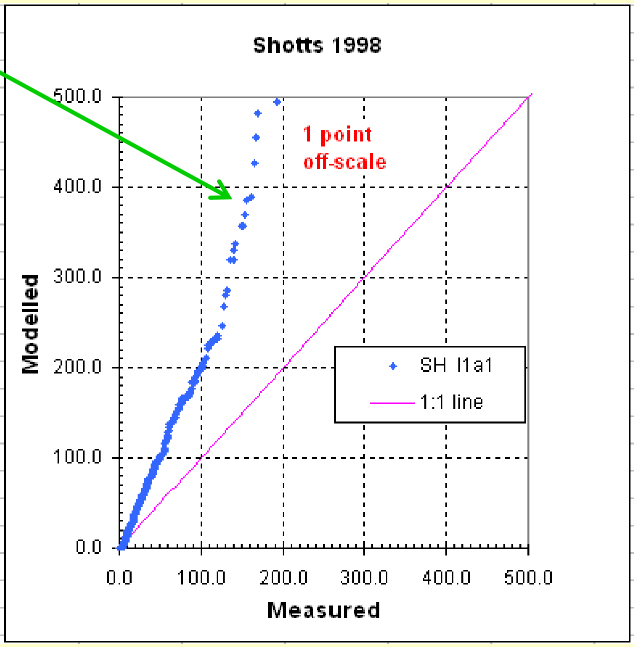


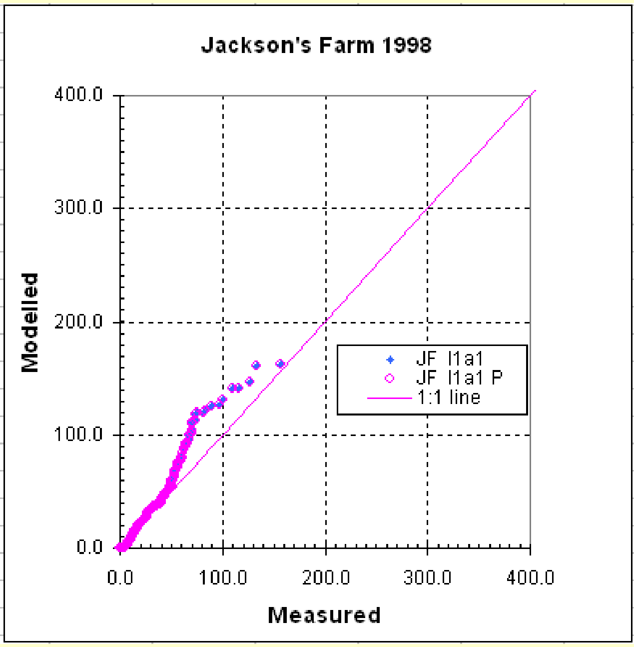
CALPUFF l1a1 (as per j1a1)

- measured met from W2 36m over forest, wind extrapolated (biases -1)
- cld from D'brook, geo and temp profile (24/day) from TAPM v403

This slide included for interest – CALPUFF overestimates at the closest monitor Shotts (about 8 km from Muja Power Station).



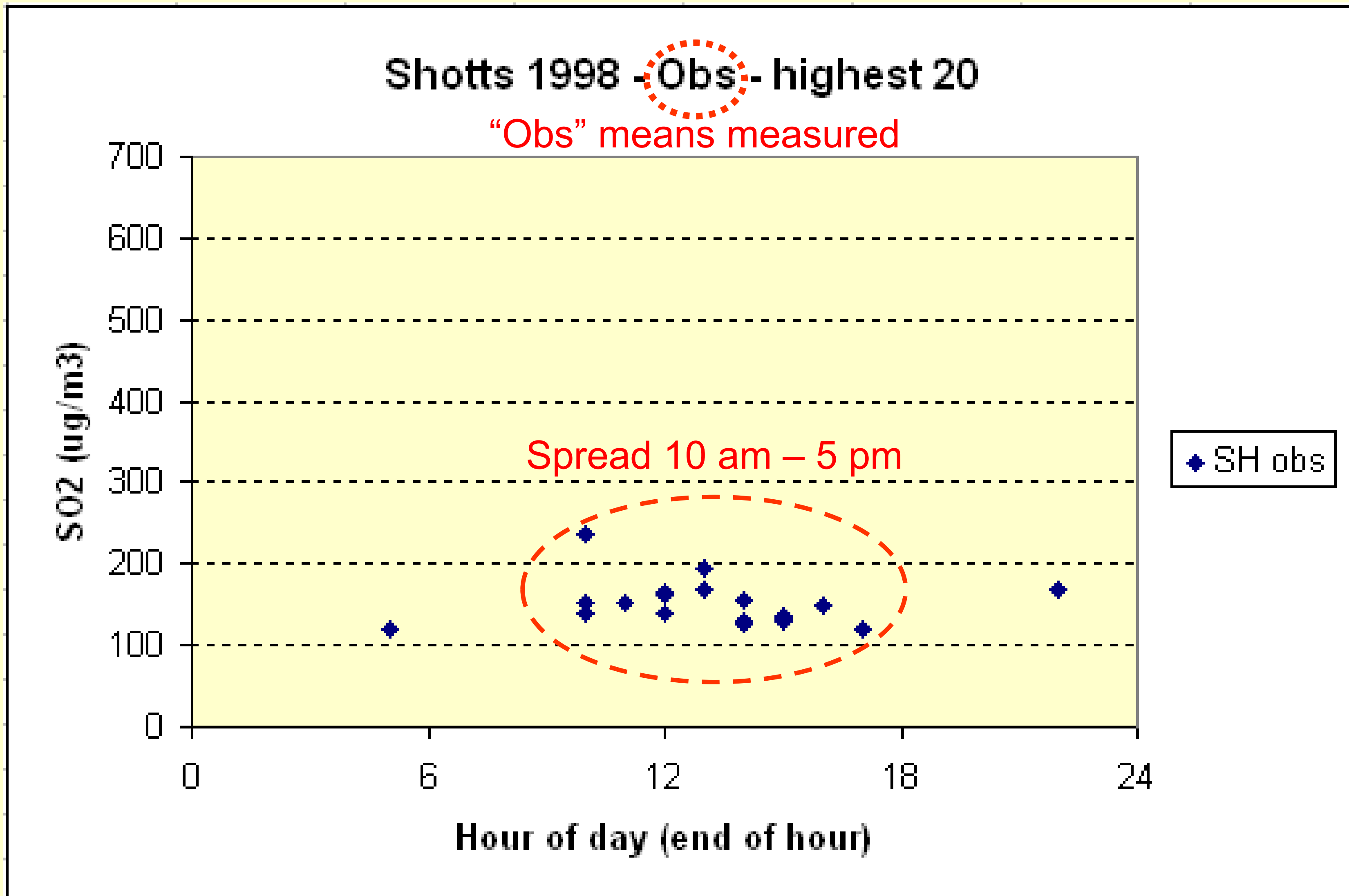




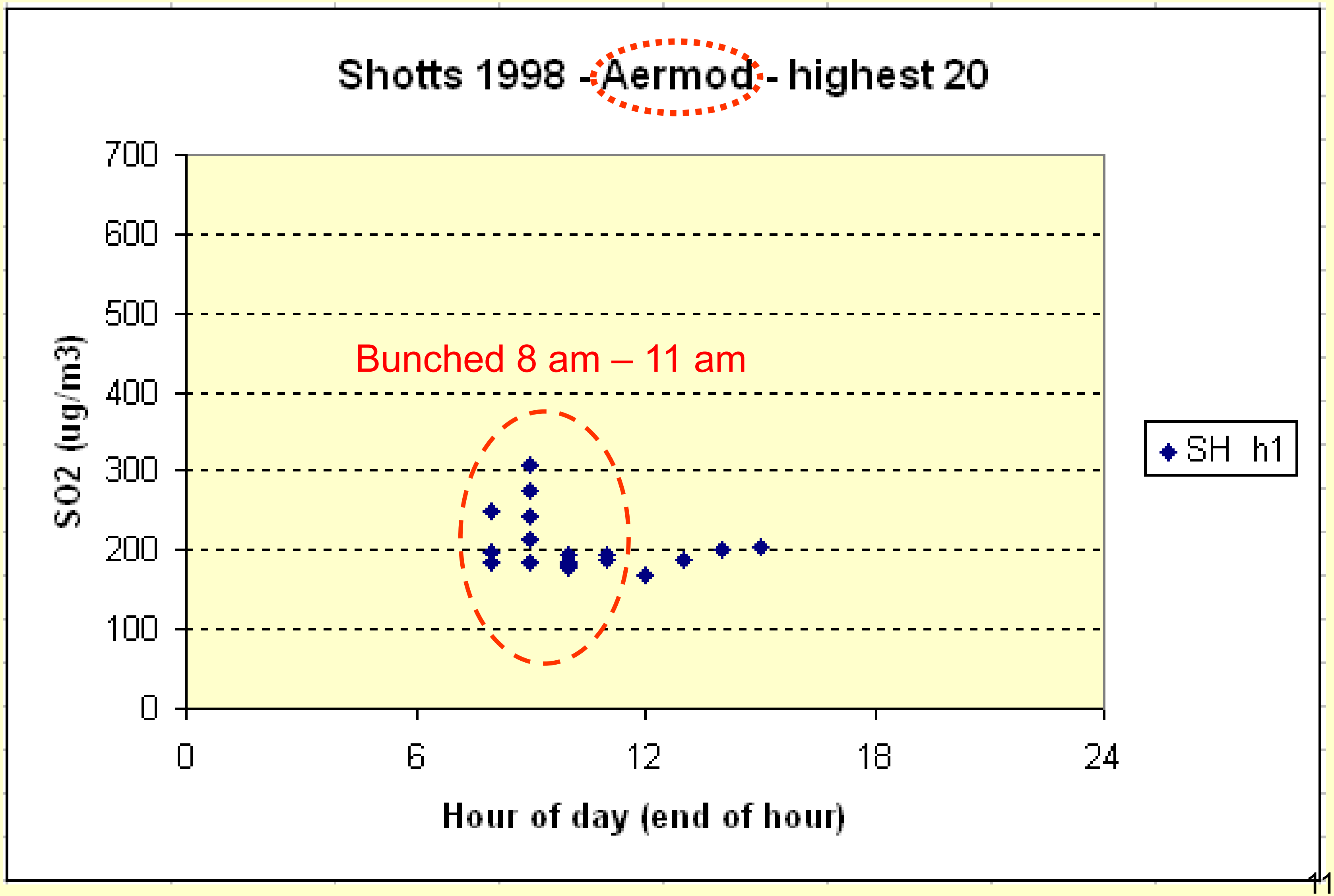
Analysis of conditions associated with top 20 concentrations at Shotts

- both AERMOD and CALPUFF give highest concentrations mid-morning under light wind unstable conditions. AERMOD tends towards very light winds and low mixing heights
- measured highest concentrations are centred on midday and occur under light – moderate winds. AERMET results for the times of these measurements indicate significantly higher values of w_* and convective mixing height than those associated with AERMOD or CALPUFF modelled peak concentrations.
- See the following graphs, alternating between measurements (“obs”) and AERMOD run h1 results

Analyses of top 20 concentrations

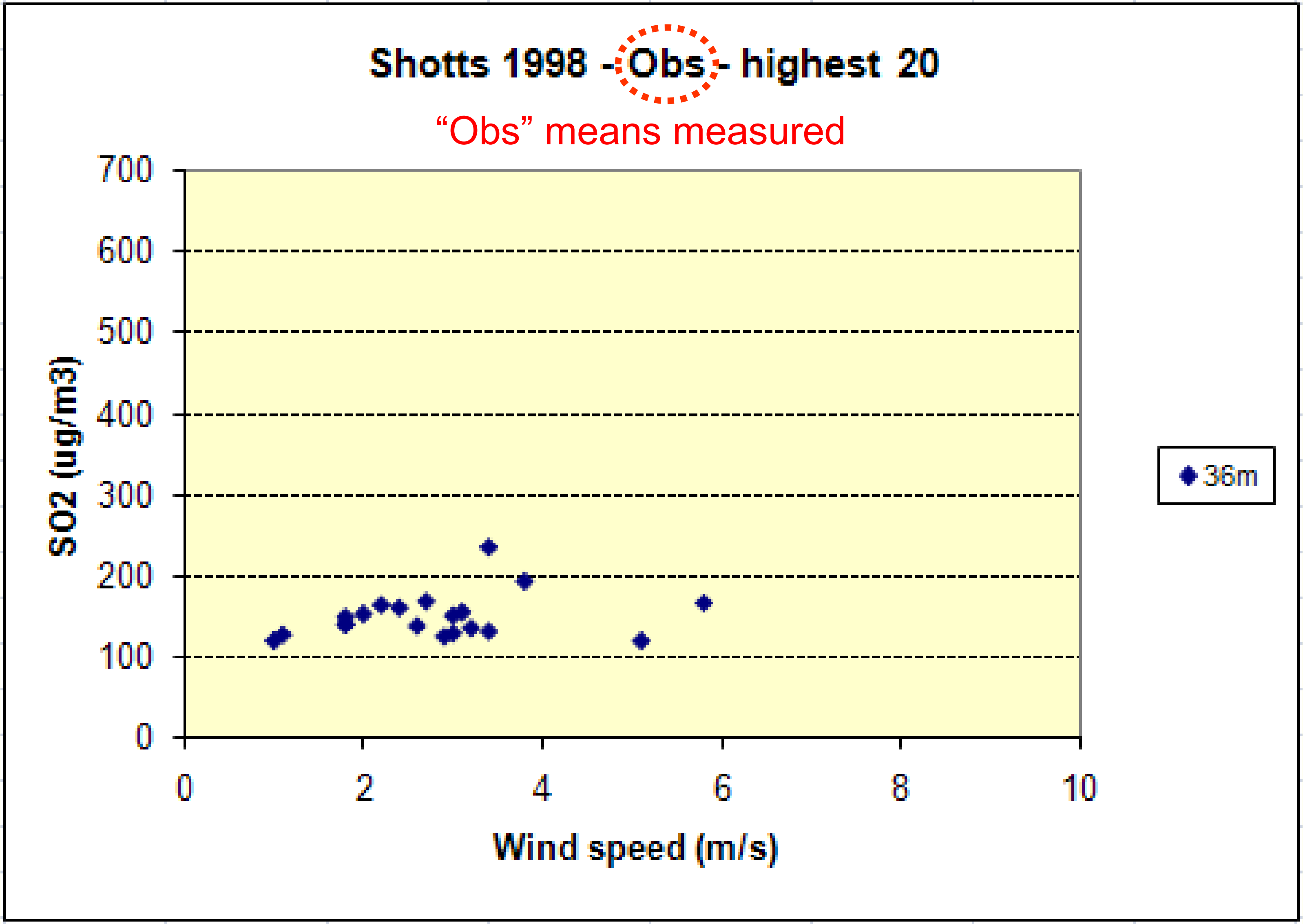


Analyses of top 20 concentrations

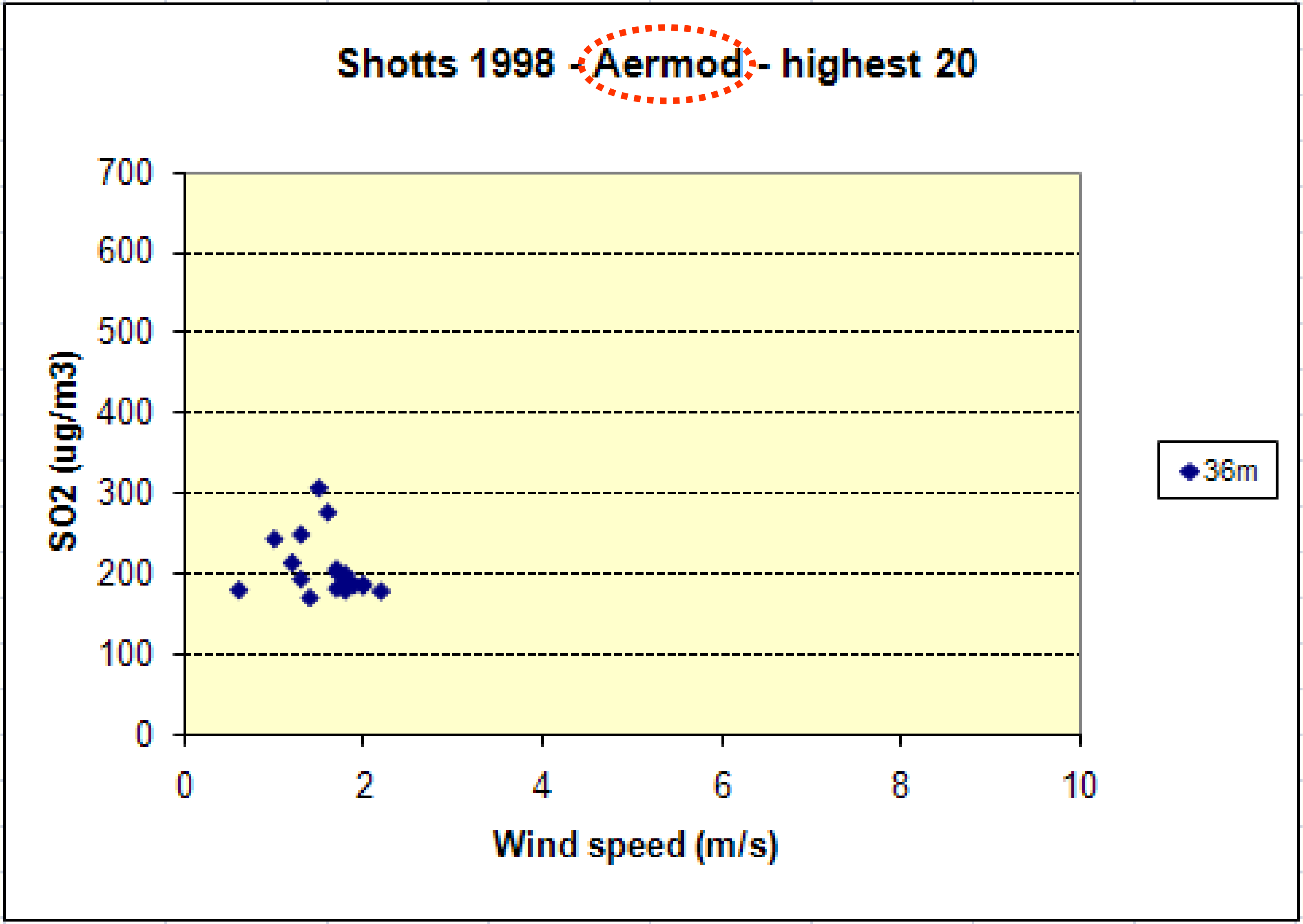


Analyses of top 20 concentrations

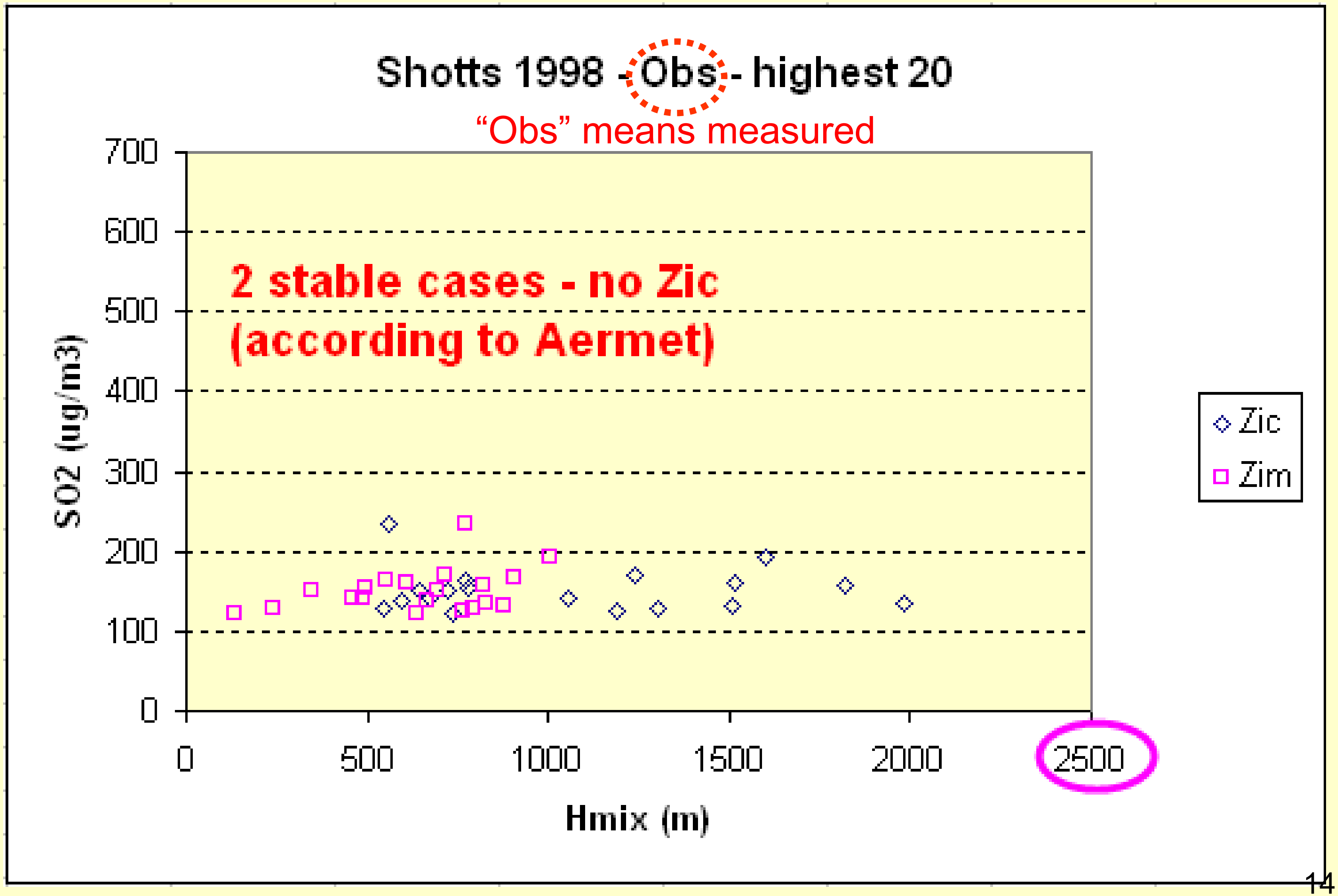
winds measured at 36 metres



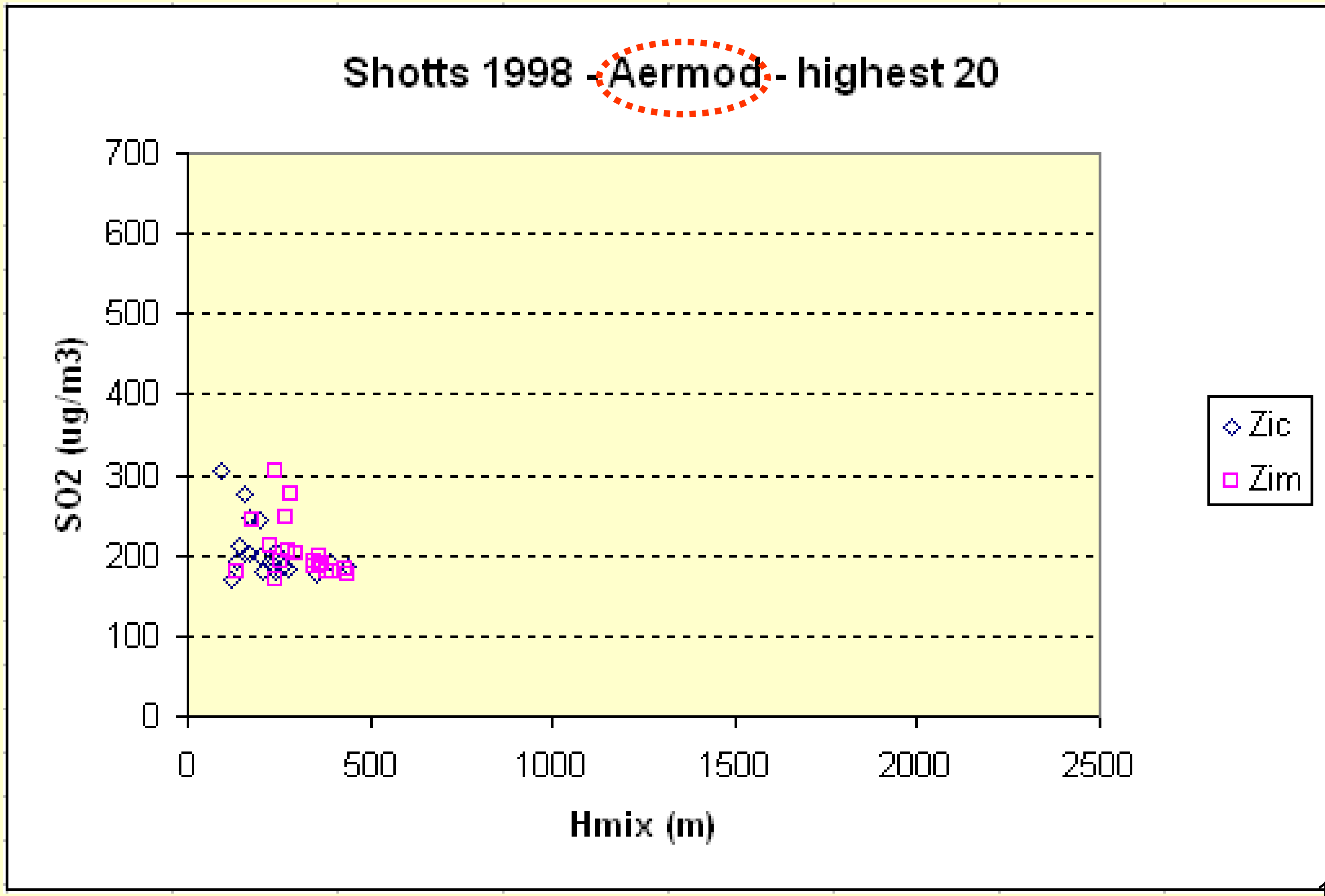
Analyses of top 20 concentrations



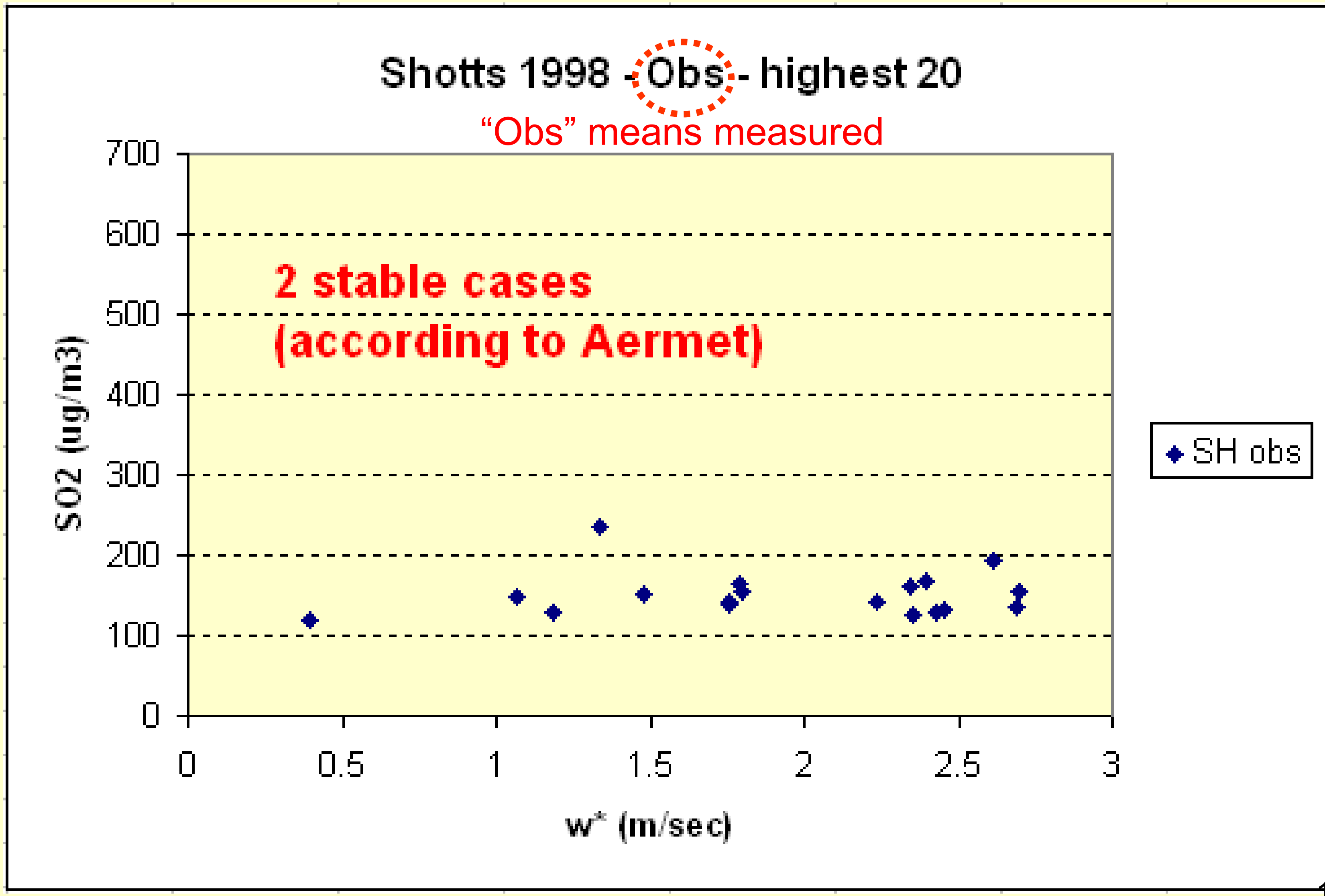
Analyses of top 20 concentrations



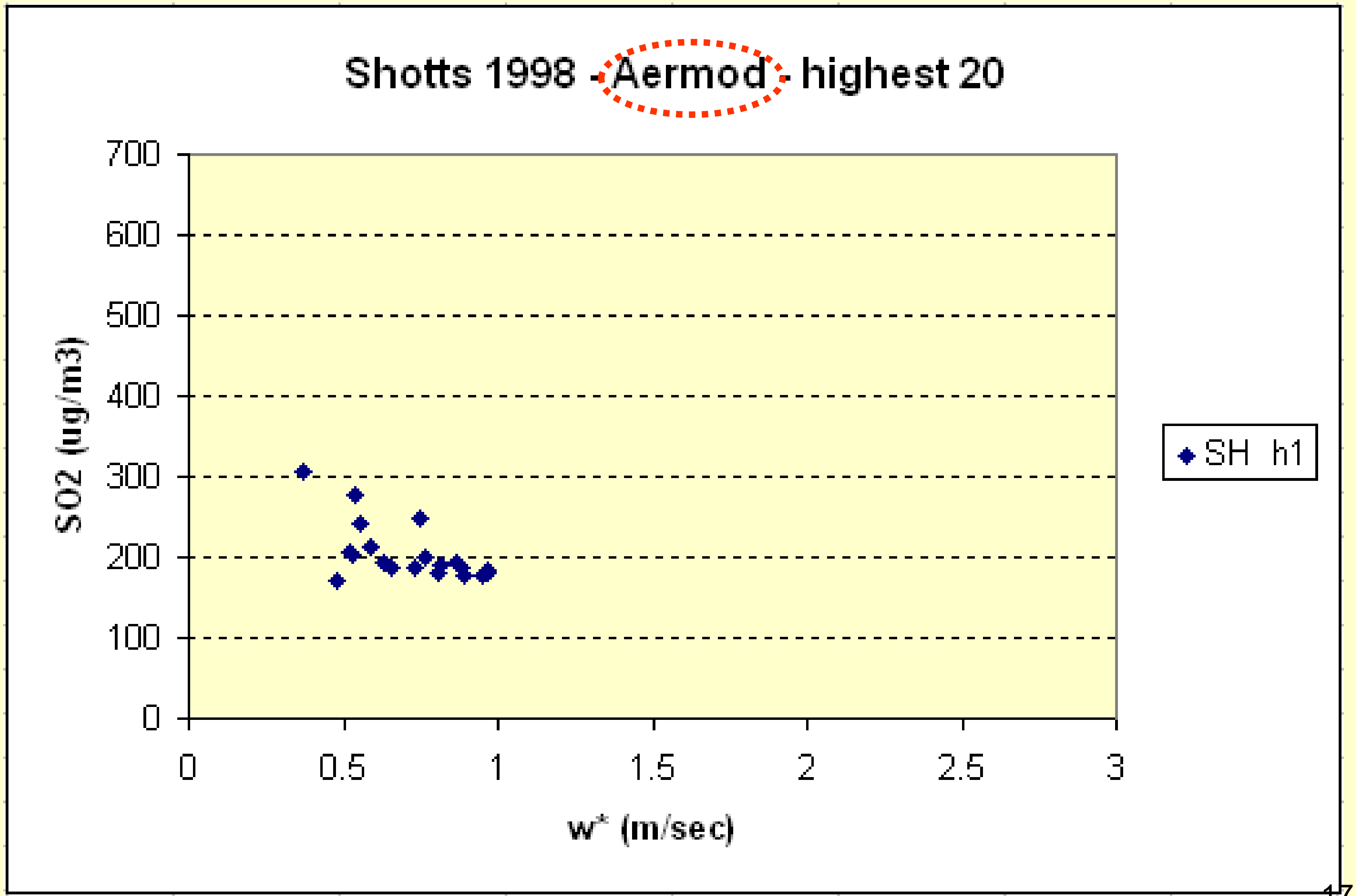
Analyses of top 20 concentrations



Analyses of top 20 concentrations



Analyses of top 20 concentrations

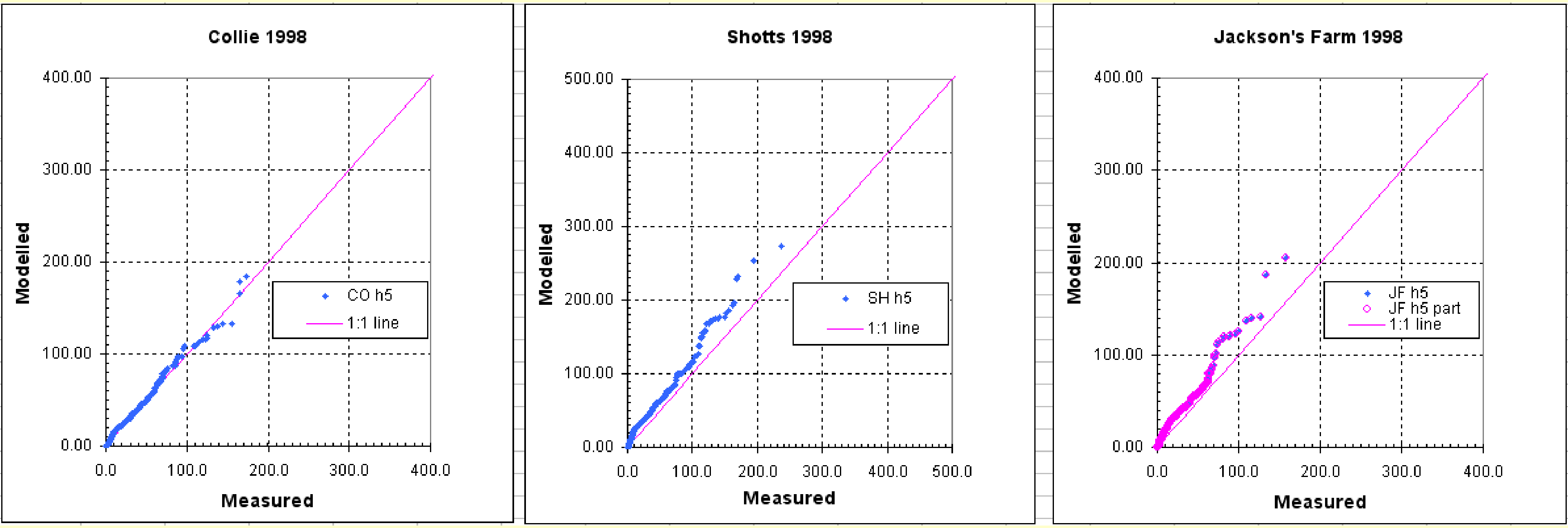


Further assessment of conditions associated with highest concentrations at Collie.

- The series of slides below show QQ plots, firstly for run h5 (see above) for all hours of 1998 and then, in subsequent slides, re-plotted for subsets of the modelled and measured concentrations obtained by separately filtering these concentrations for specified ranges of parameter(s) in the coincident AERMET records, as labeled on each slide.
- (*Note – I have persisted with QQ plots, paired in space but not in time. Comments on method welcome.)*

AERMOD run h5 (1998) (repeated)

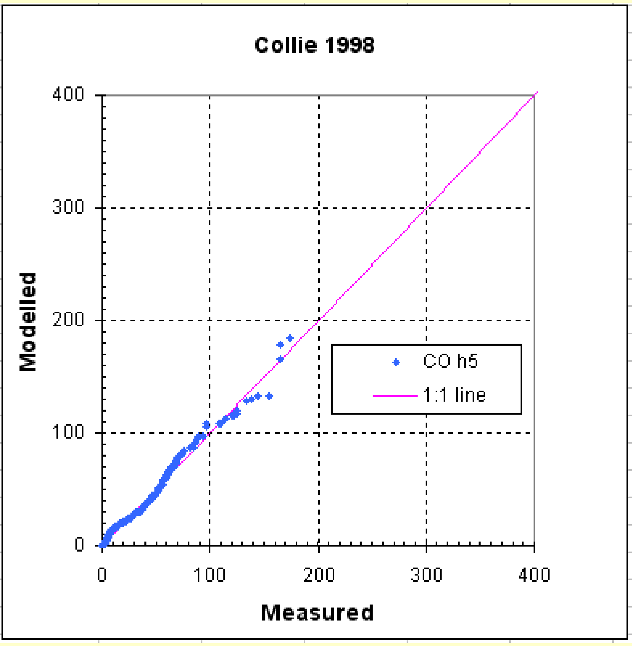
- measured meteorology (36m over forest), calculated solar radiation
- observed cloud from remote site, temperature profiles from TAPM (prognostic model)
- SRTM terrain data (terrain effects minor at Collie; stack height > 2 x terrain variation)
- all hours (no filtering for particular conditions)

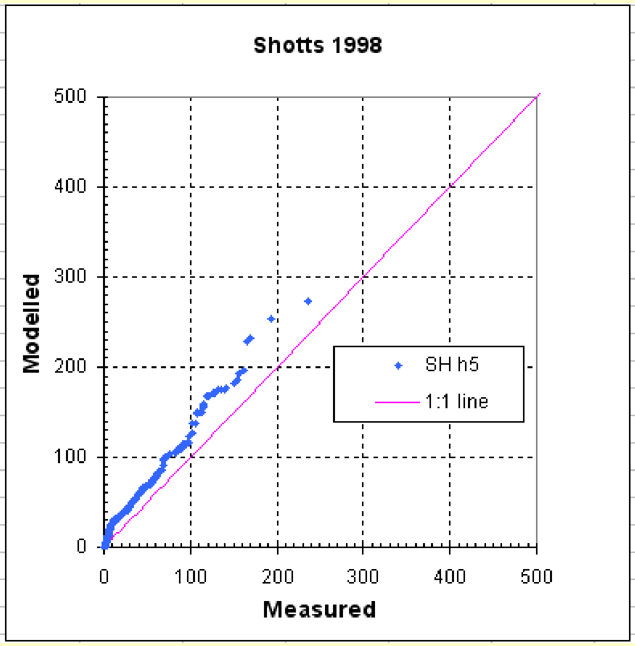


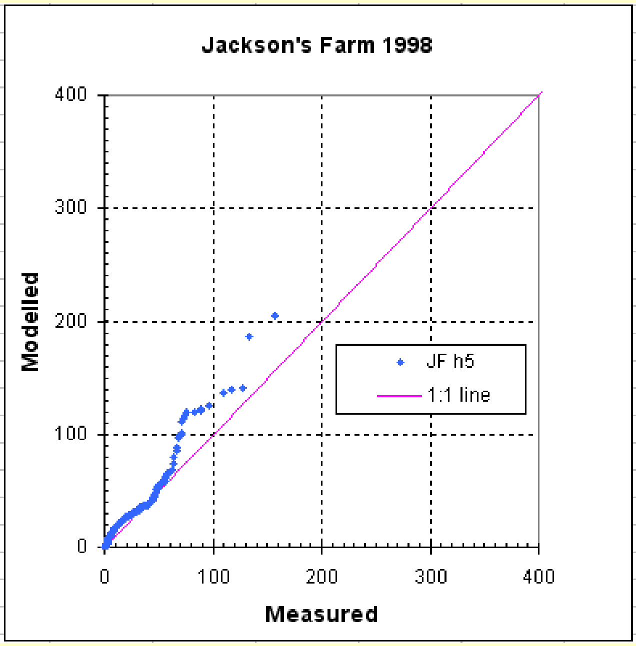
Is this apparently good model/measurement comparison for "all hours" a product of compensating under/over-estimates in particular conditions? See following slides.

AERMOD run h5 (1998)

- unstable conditions



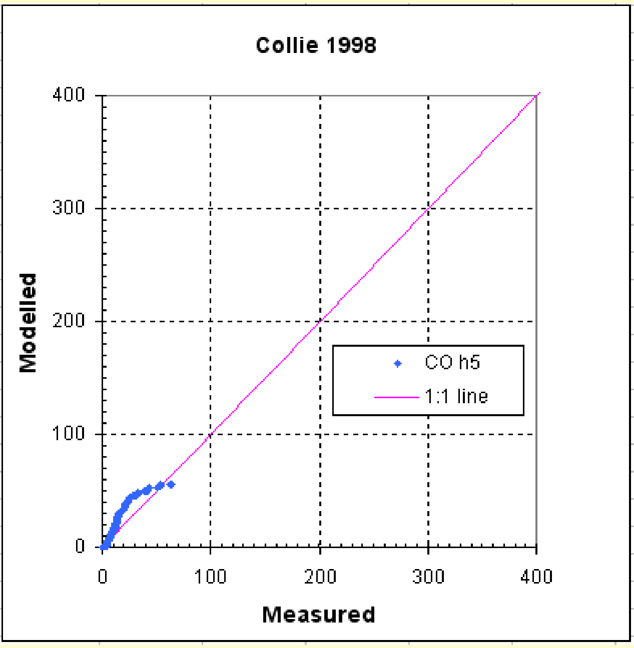


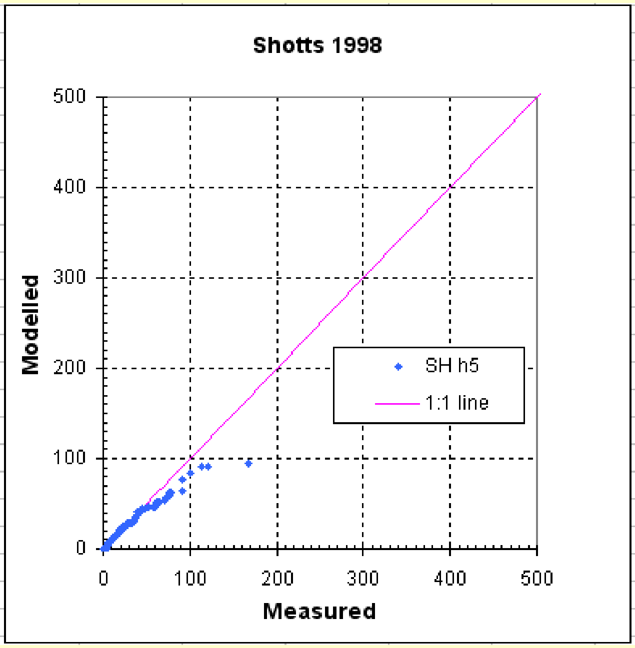


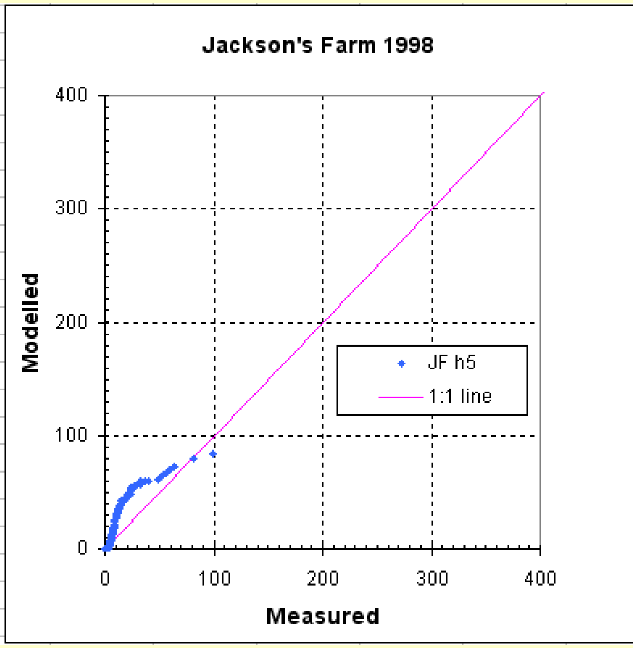
Very similar for high concentrations to "all hours". Highest concentrations clearly occur under unstable conditions (see next plot).

AERMOD run h5 (1998)

- stable conditions

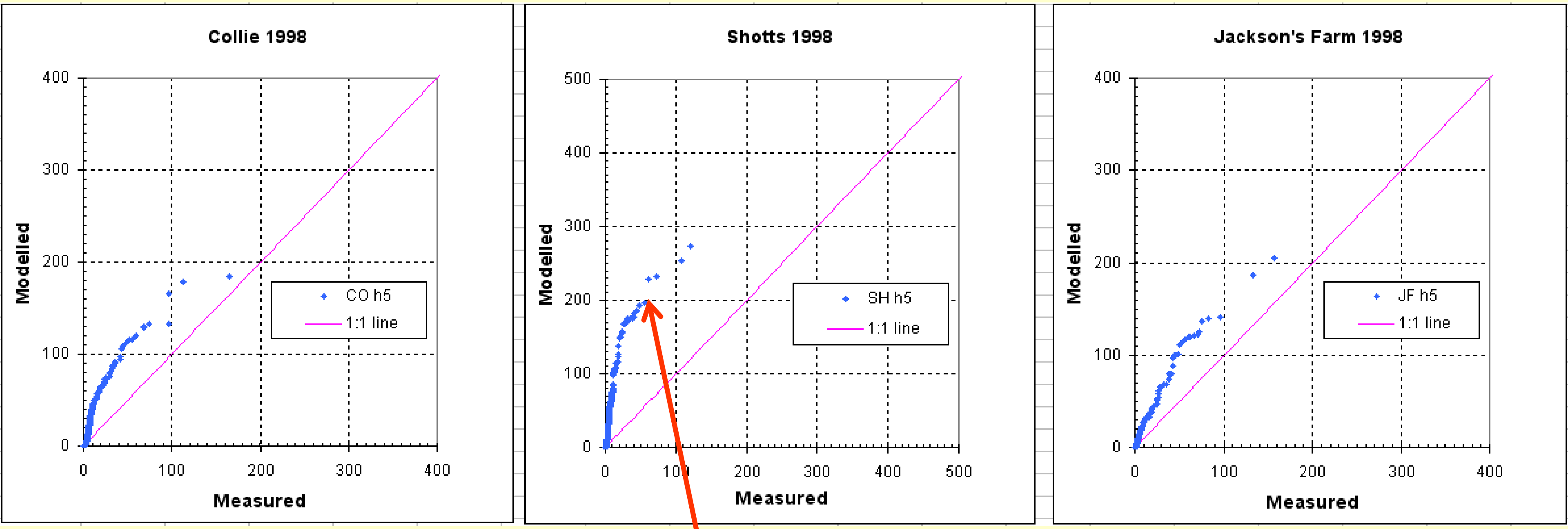






AERMOD run h5 (1998)

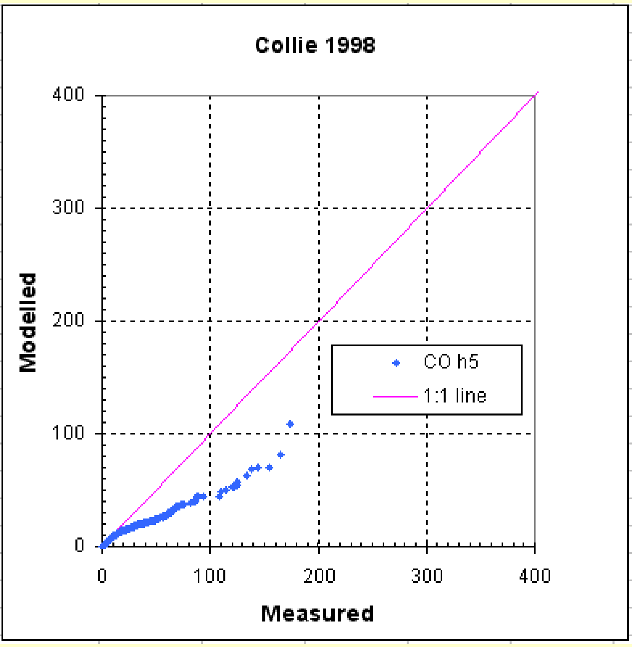
- convective mixing is mild (0 < w* < 1)

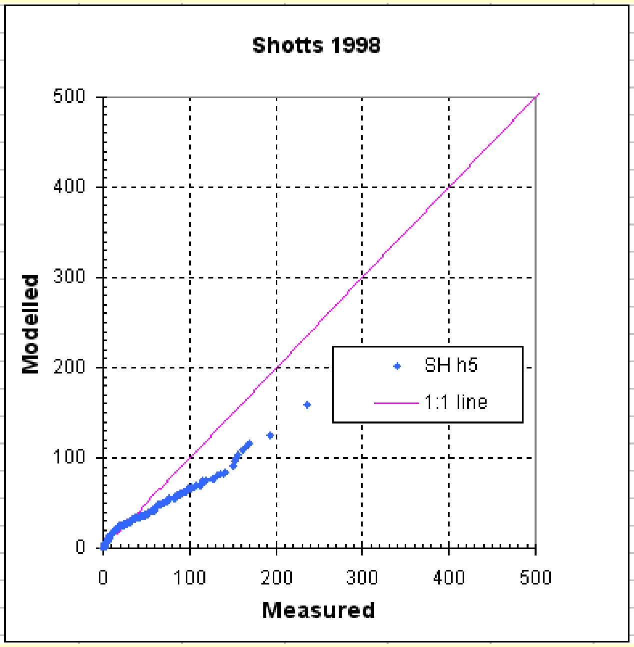


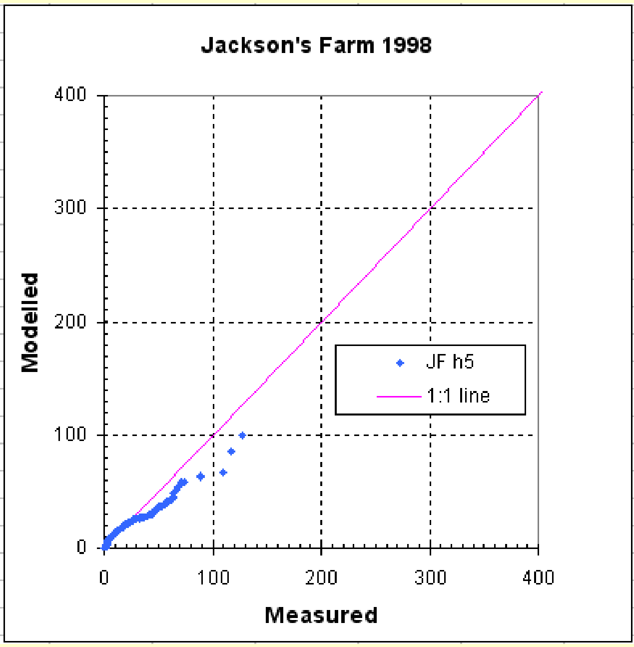
Model over-estimation, notably at Shotts

AERMOD run h5 (1998)

- convective mixing is moderate to strong (w* > 1)



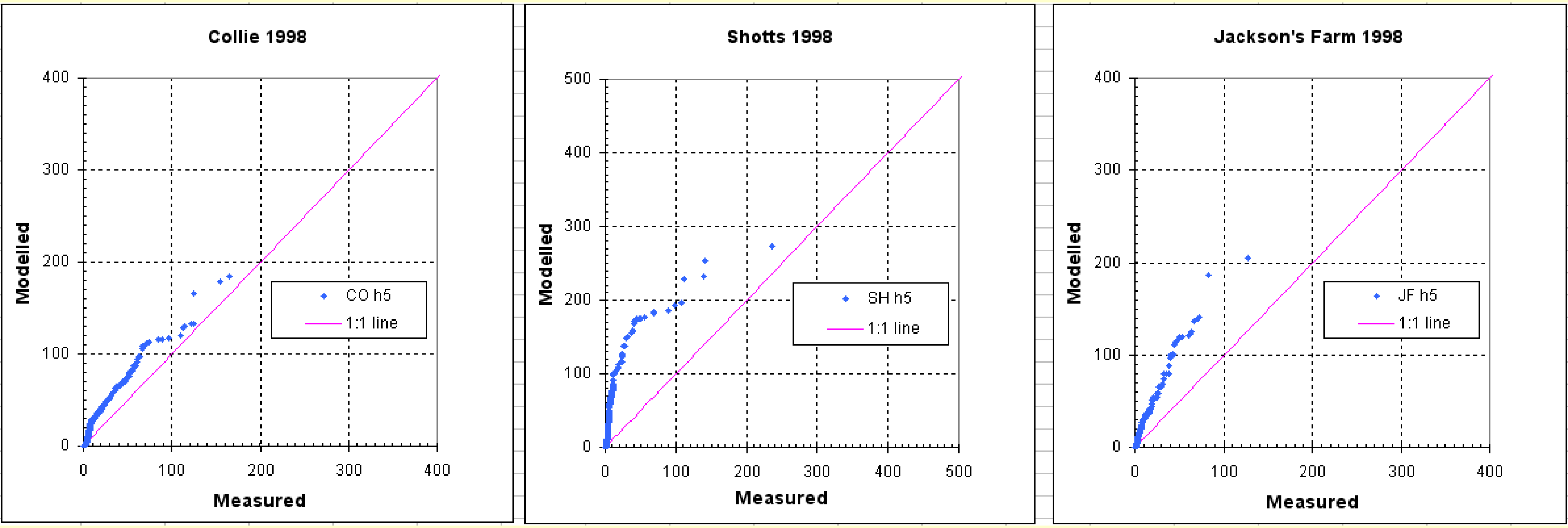




Model under-estimation

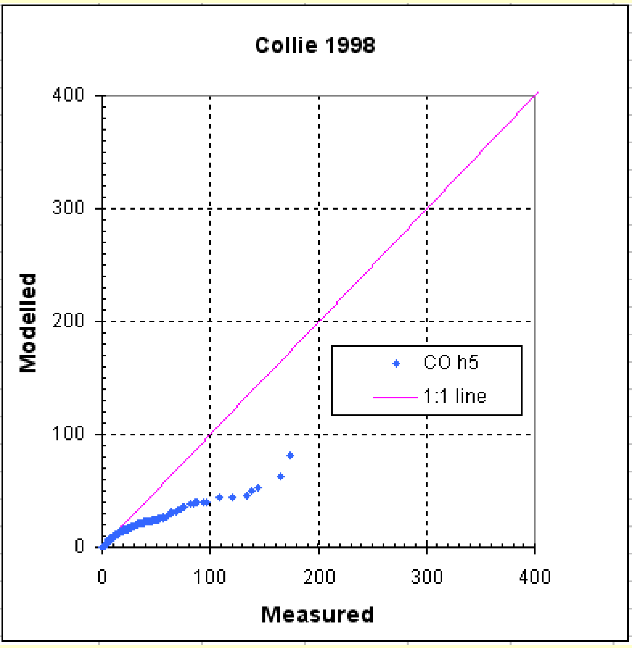
AERMOD run h5 (1998)

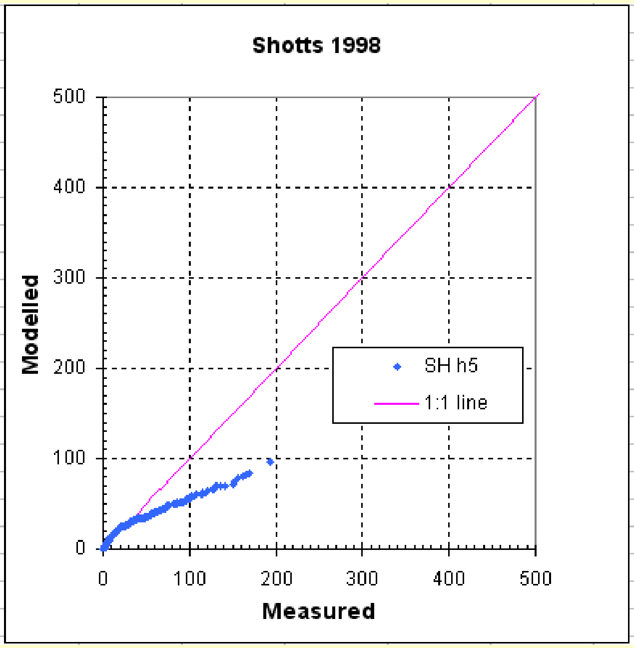
- convective mixing height Zic between 0 and 600 m *(related to w_*)*

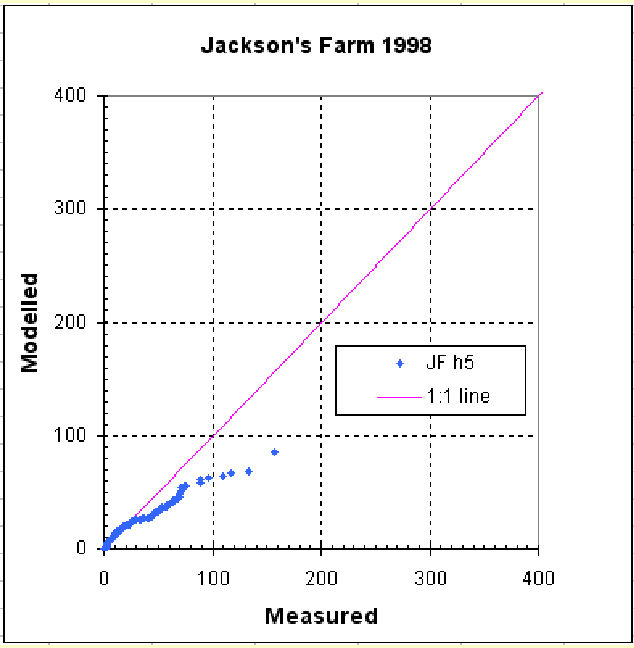


AERMOD run h5 (1998)

- convective mixing height Zic greater than 600 m

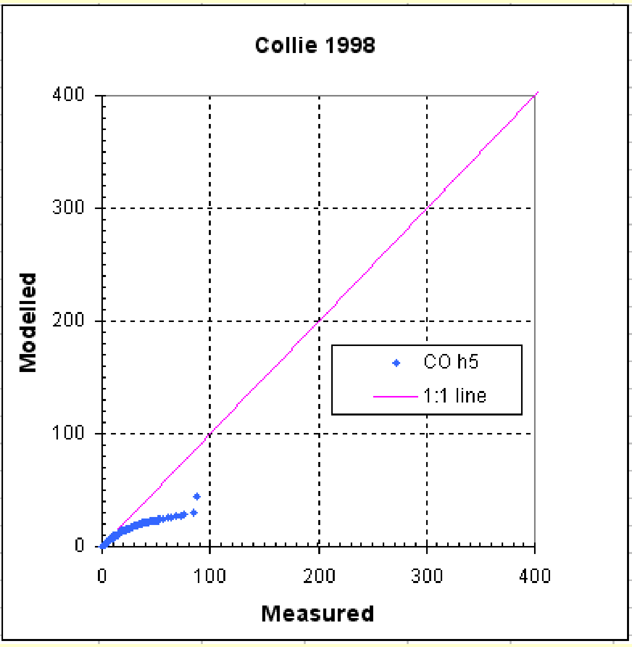


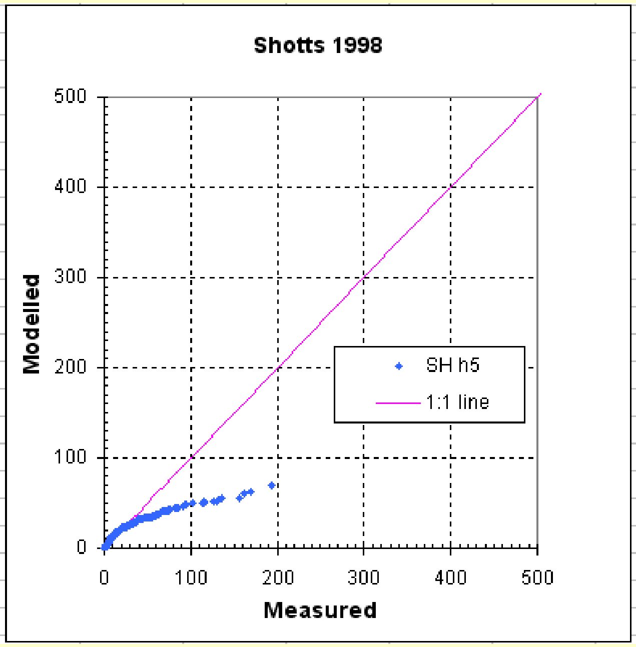


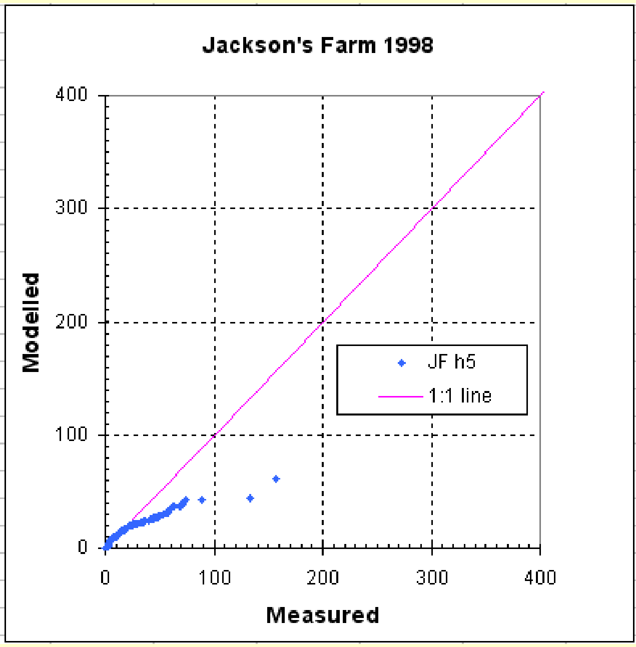


AERMOD run h5 (1998)

- convective mixing height Zic greater than 900 m



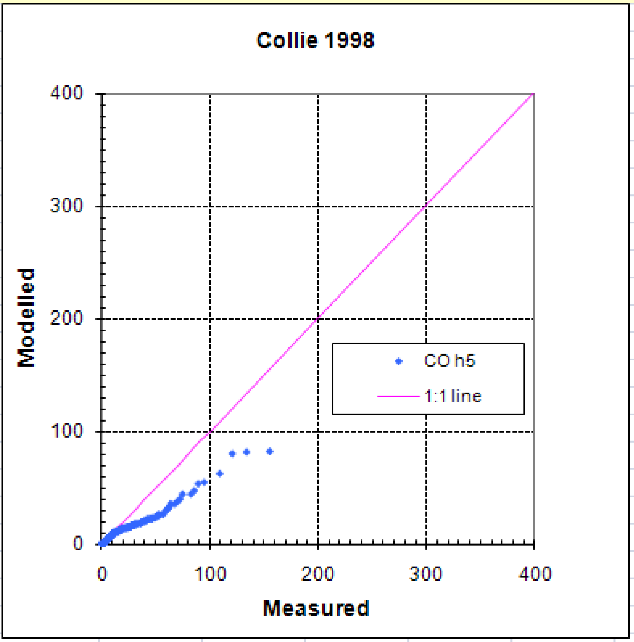


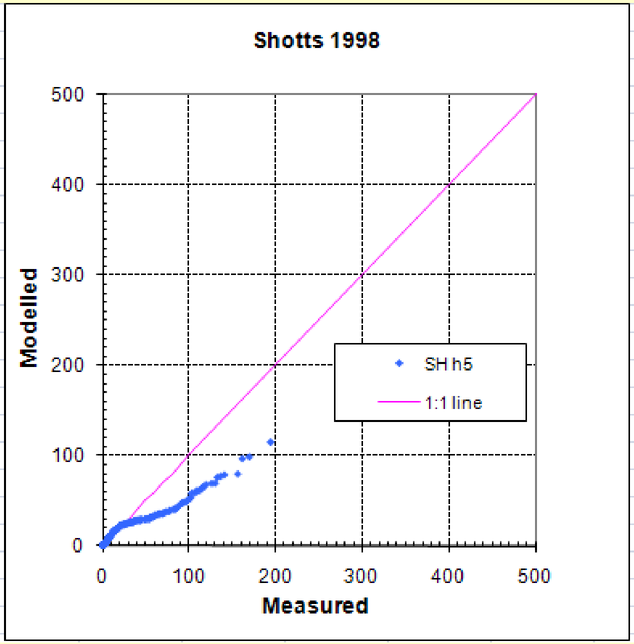


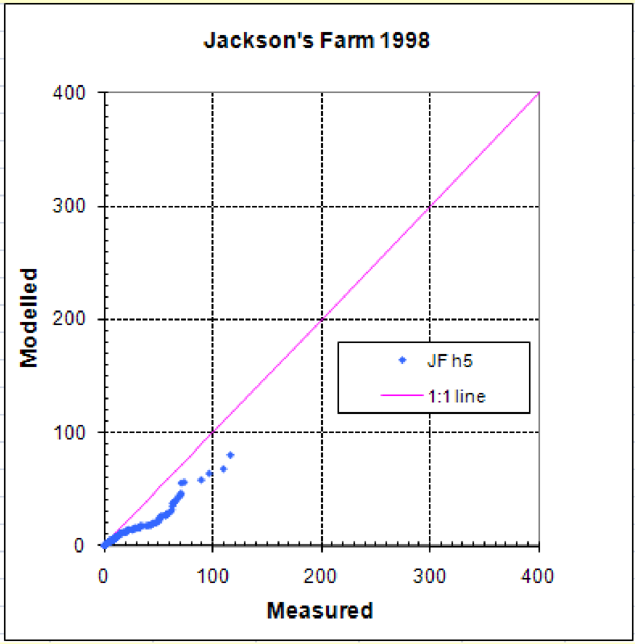
Under-estimation occurring when mixing height is large, which should be relatively simple conditions for AERMOD. Has this been seen in other studies?

AERMOD run h5 (1998)

- hours ending 11 to 17 inclusive, air temperature > 20°C







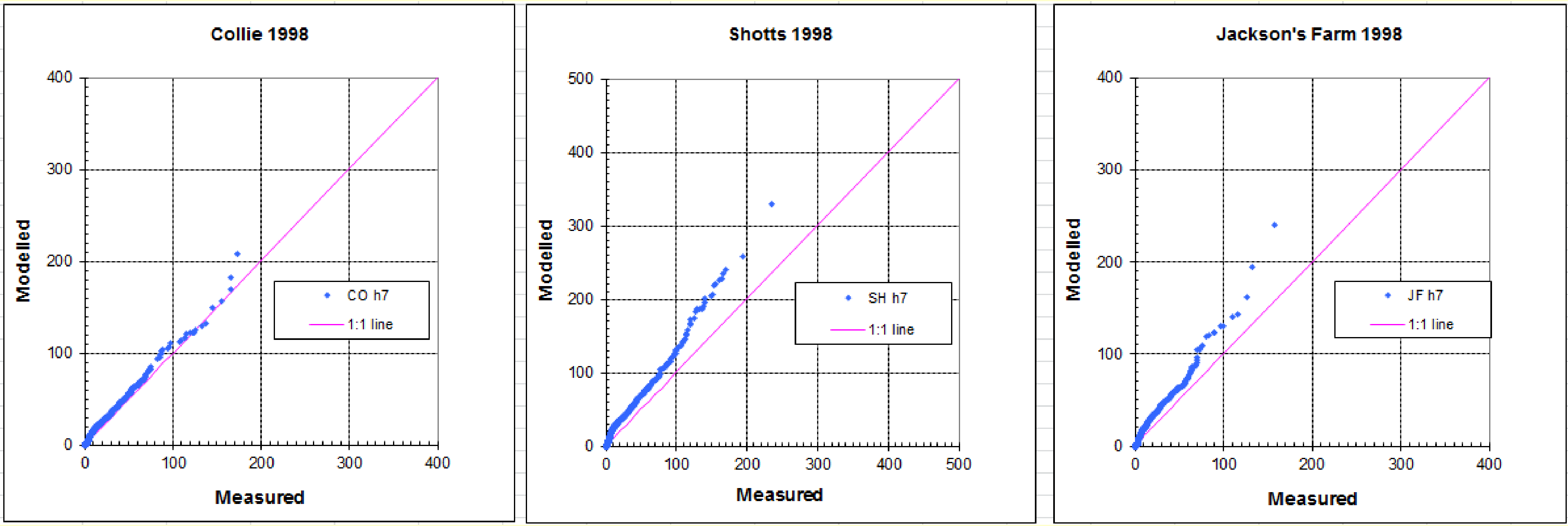
Filtering here is for <u>simple parameters (time, temperature),</u> not using AERMET-calculated parameters. Confirms under-prediction in what should be straight-forward conditions for dispersion modelling (warm day, late morning to afternoon).

Sensitivity of the foregoing filtering results to meteorological data used in AERMET / AERMOD

- Historical Collie data do not include cloud cover or temperature soundings.
- The foregoing model run h5 used questionable cloud observations and temperature profiles from the prognostic model TAPM.
- AERMET / AERMOD were re-run using:
  - All measurements:- as per h5 but with temperature soundings from Perth airport, 160 km NNW. QQ plots for all hours were very similar to the foregoing run h5.
  - All TAPM-generated input:- (TAPM produces AERMET-format files for direct input to AERMOD, bypassing AERMET). QQ plots for all hours showed moderated over-estimation.
- QQ plots for filtered cases from these additional two AERMOD runs showed the same patterns of over and under-estimation for variations in w_*, etc. *(Selected plots included below).*
- Suggests the behavior is characteristic of AERMOD (a resilient issue).

AERMOD run h7 (1998)

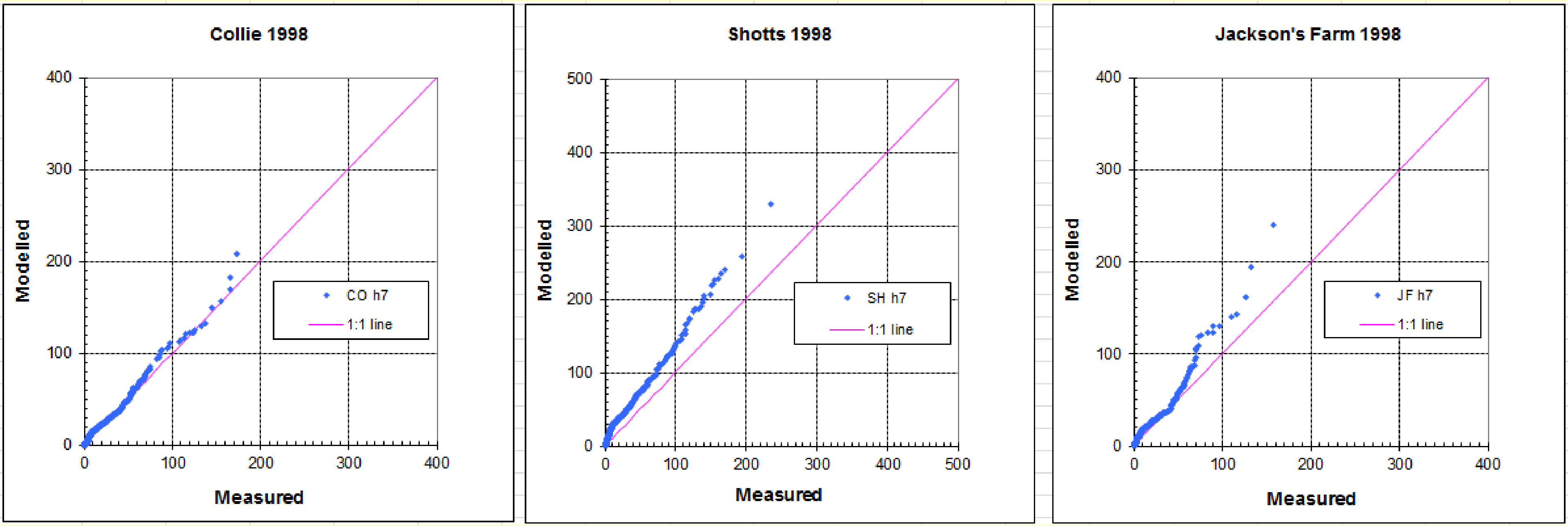
- measured meteorology (36m over forest), calculated solar radiation
- observed cloud from remote site, temperature soundings Perth Airport 160 km NNW
- terrain not included (minor factor)
- all hours (no filtering for particular conditions)



Very similar to H5 all hours, despite using remote sounding data.

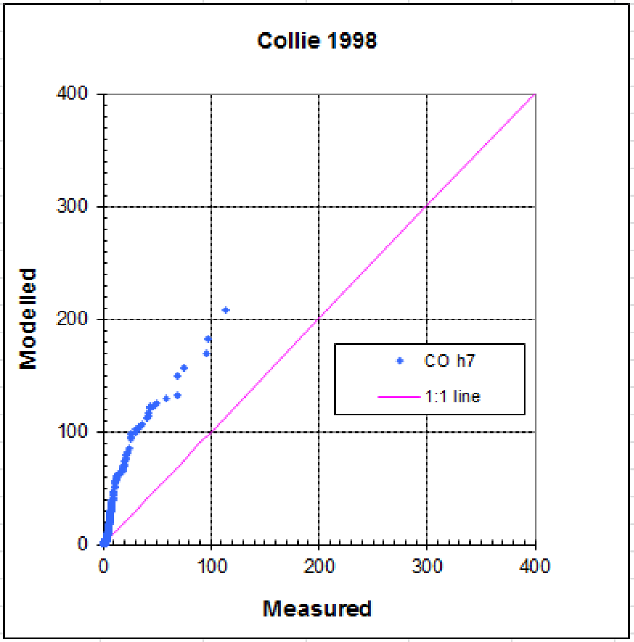
AERMOD run h7 (1998)

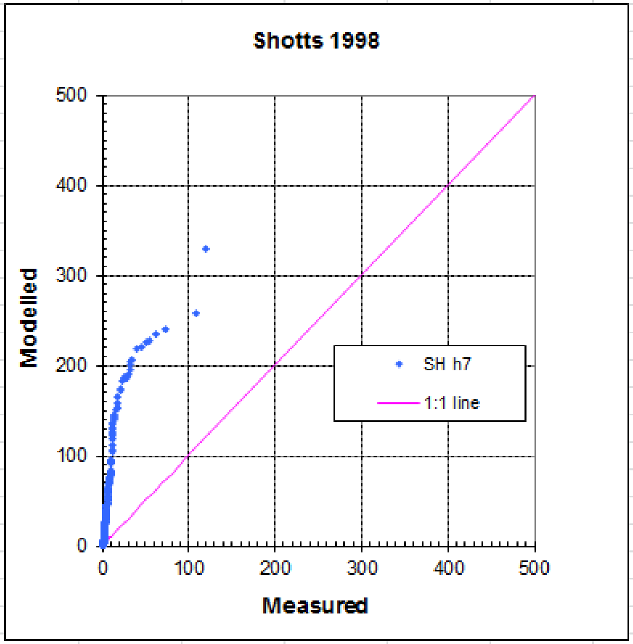
- unstable conditions

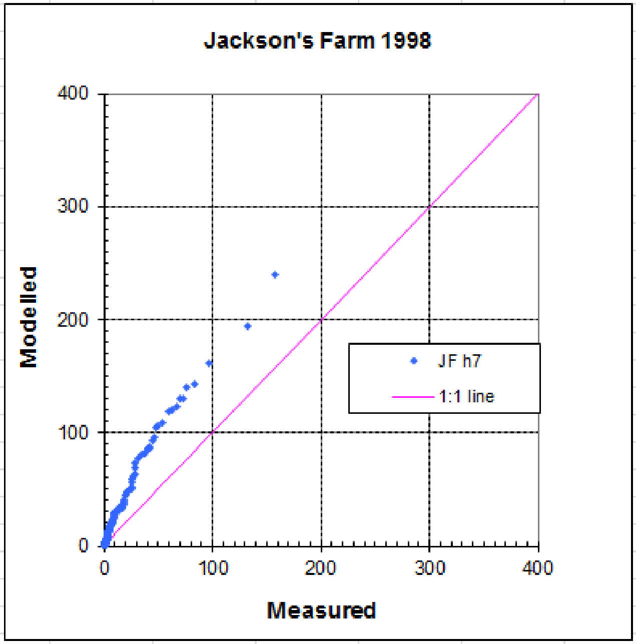


c.f. h7 all hours - unstable conditions dominate high concentrations

AERMOD run h7 (1998)
- convective mixing is mild (0 < w* < 1)



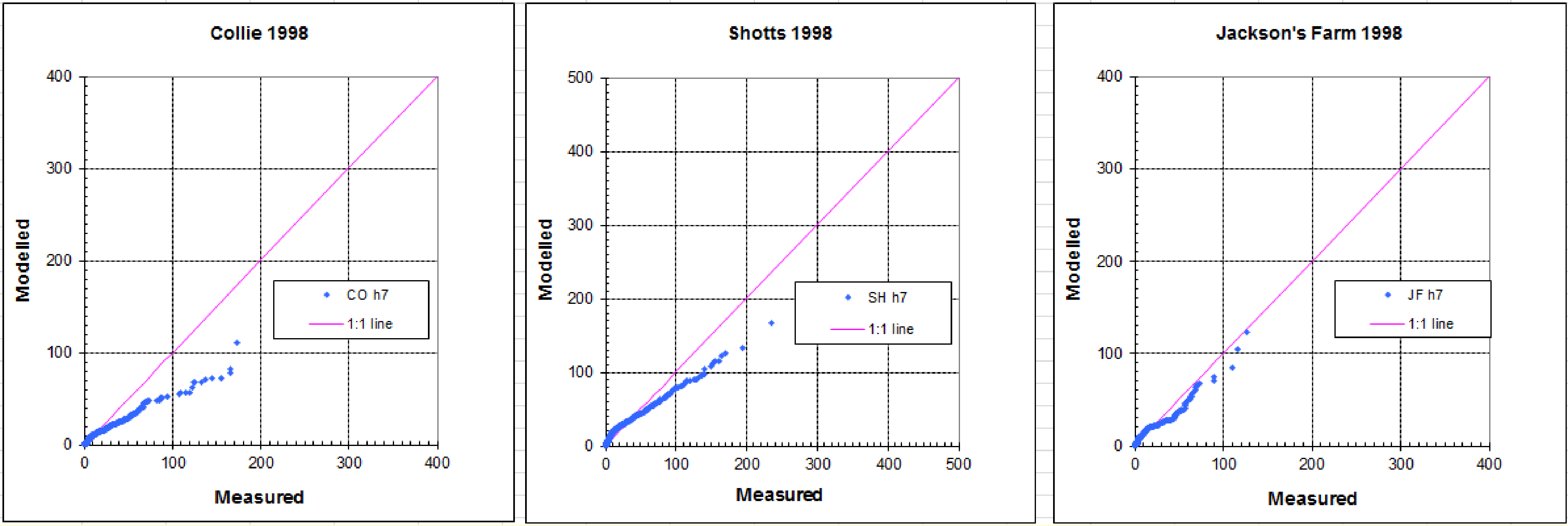




model over-estimation in mildly convective conditions, notably at Shotts

AERMOD run h7 (1998)

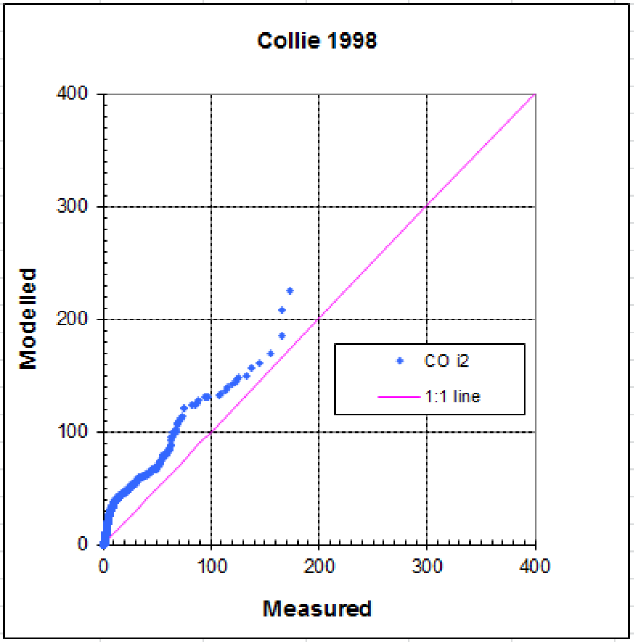
- convective mixing is moderate to strong (w* > 1)

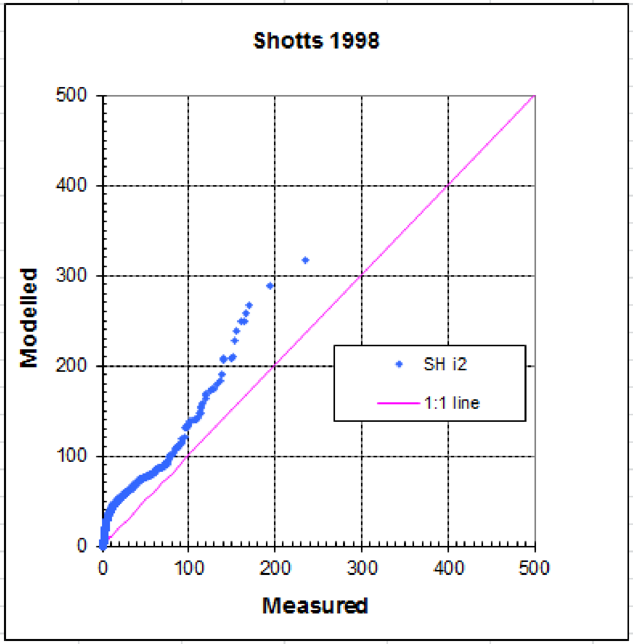


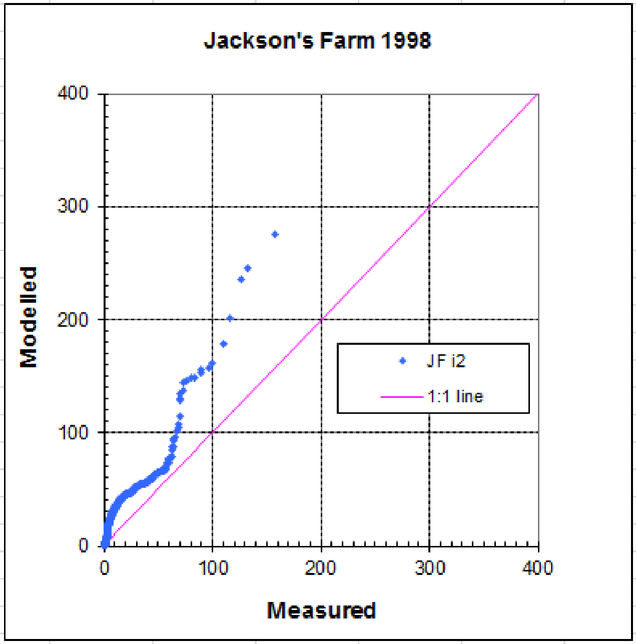
model under-estimation

AERMOD run i2 (1998)

- mesoscale model TAPM meteorology (no measurements)
- TAPM produces AERMET-format .sfc and .pfl files
- .pfl file reduced to surface level wind and temperature only (no upper levels, no turb.)
- all hours (no filtering for particular conditions)



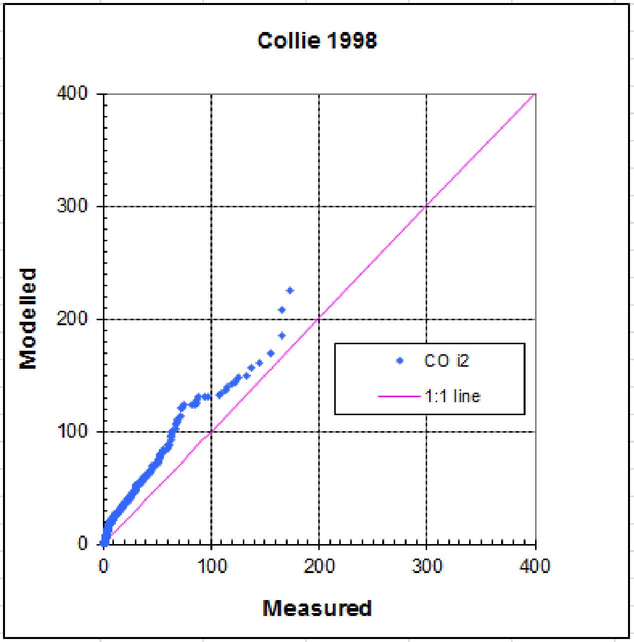


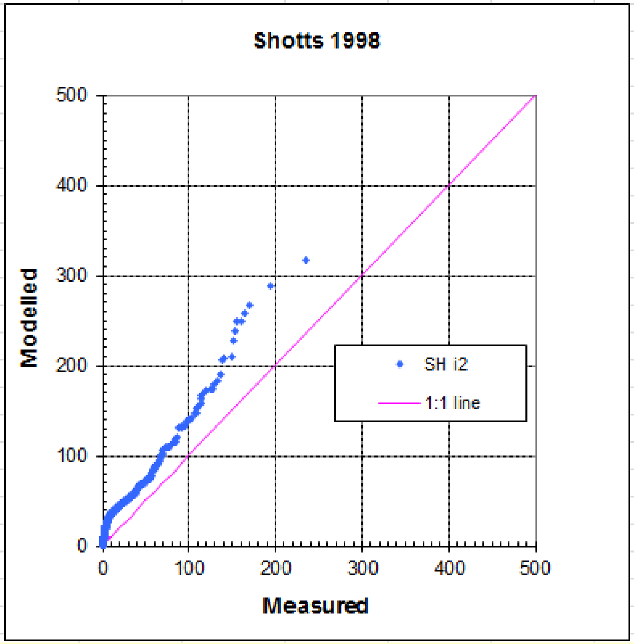


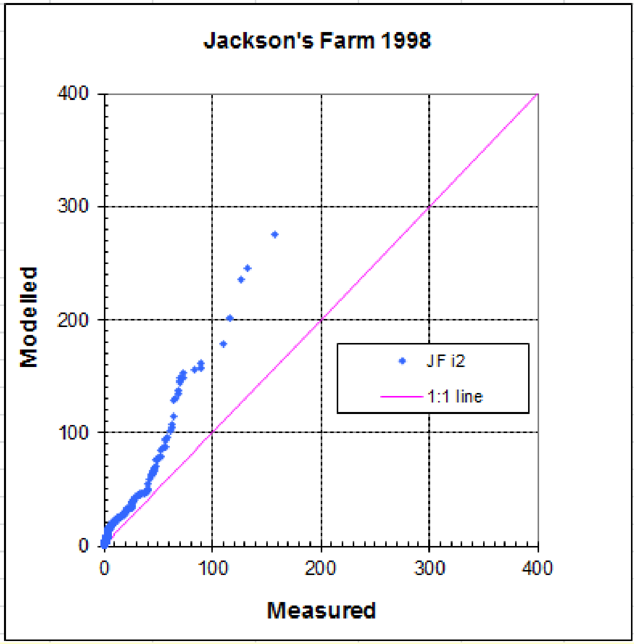
moderate over-estimation c.f. runs h5 and h7.

AERMOD run i2 (1998)

- unstable conditions



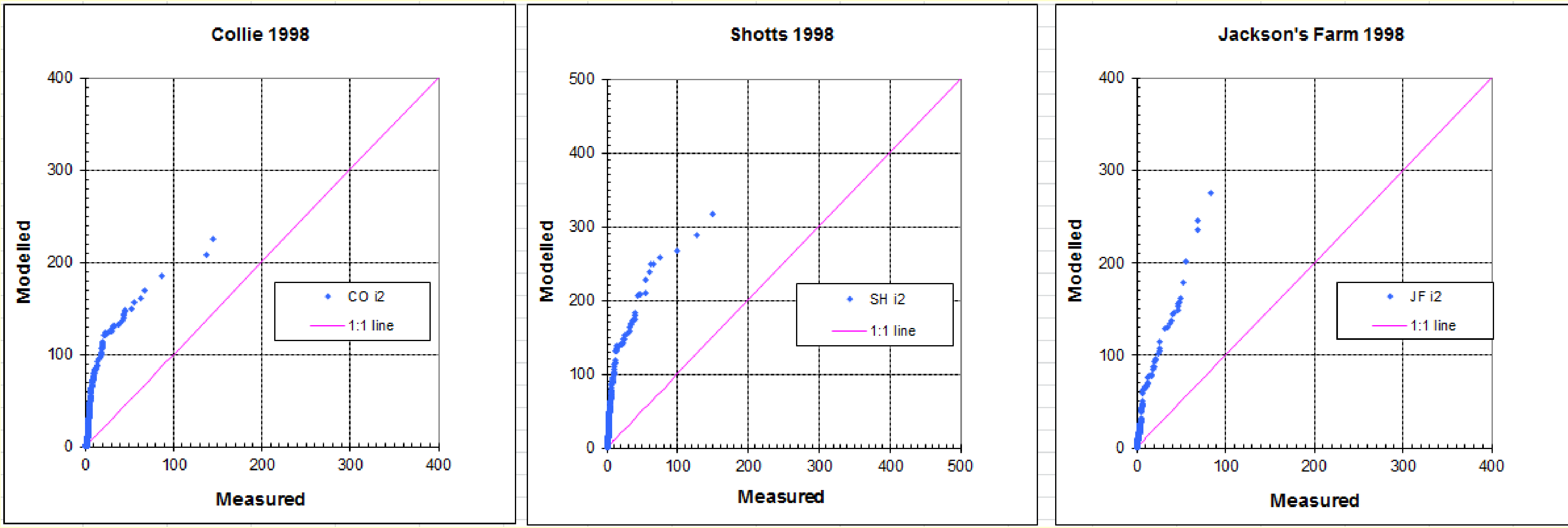




c.f. i2 all hours - unstable conditions dominate high concentrations

AERMOD run i2 (1998)

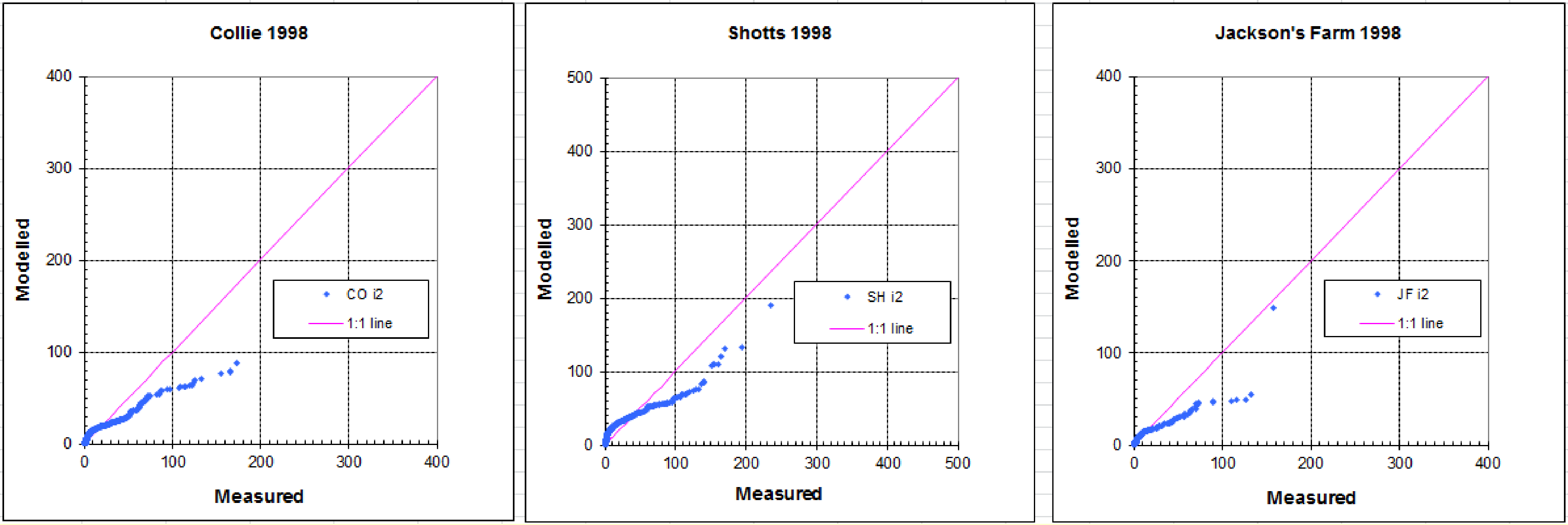
- convective mixing is mild (0 < w* < 1)



model over-estimation in mildly convective conditions at all monitoring sites

AERMOD run i2 (1998)

- convective mixing is moderate to strong (w* > 1)



model under-estimation despite over-estimation for all hours and unstable hours

AERMOD's three plume scheme

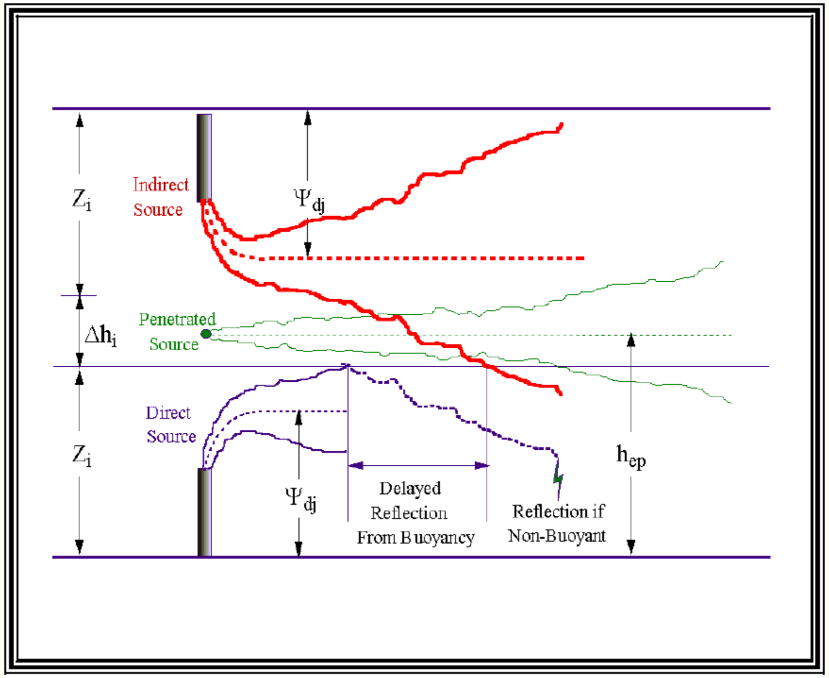


Figure 14: AERMOD's Three Plume Treatment of the CBL

- *AERMOD's penetrated plume has been found (from debug output) to be a dominant cause of highest concentrations at Collie and Caversham (further evidence follows);*
- *AERMOD has no memory from one hour to the next;*
- *must calculate the concentration from a penetrated plume in the hour it penetrates even though it may not mix to ground in that hour;*
- *in reality, by the time it mixes to ground, the meteorology would be different, notably the turbulent mixing would be greater;*
- *the scheme must therefore be "tuned" to give a representative magnitude of concentrations, recognising that the time of occurrence will not be generally correct.*
- *How well has it been tested? Might it become unreliable for various ranges of met conditions, plume buoyancy, distance-time, etc?*

AERMOD's three plume scheme cont...

The AERMOD MFD discussion of dispersion in the CBL references Weil Corio and Brower (1997). It is not clear whether the penetrated plume dispersion scheme came from that reference, but Jeff Weil referred to the paper in an email 23 June 2012 to Steve Hanna, forwarded to Paine and Rayner.

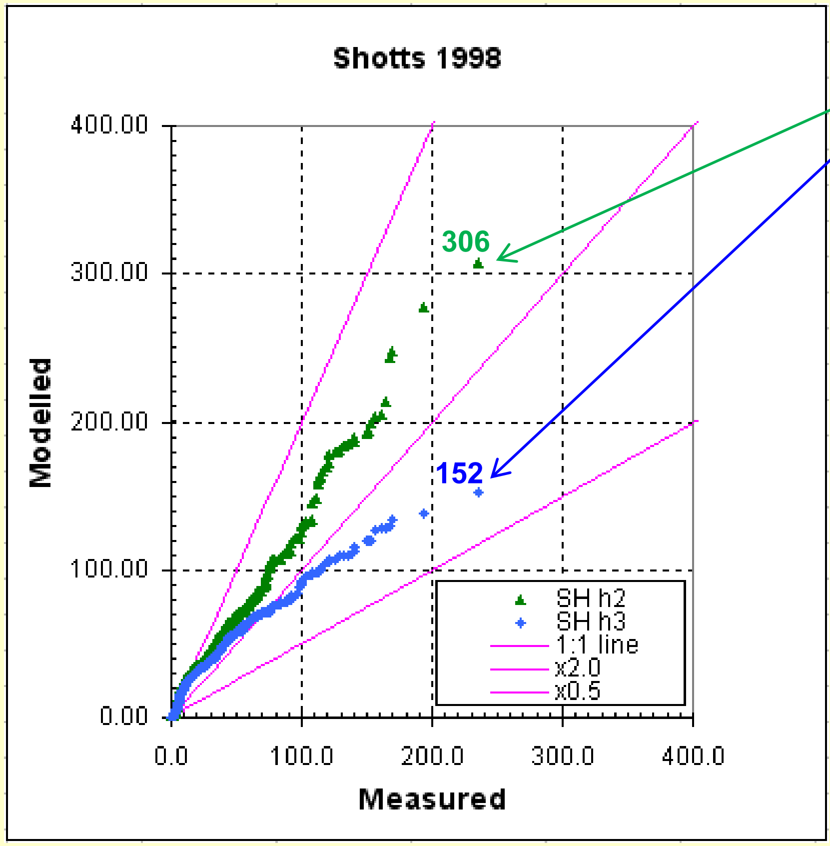
WC&B (1997) has a dispersion formulation for the penetrated plume (eq. 30) that uses the convective PDF model, whereas the AERMOD Model Formulation Document eq. 66 is Gaussian in the vertical.

- Is it likely that a Gaussian plume formulation for vertical dispersion into a growing CBL will be generally reliable?

- Is the penetrated plume formulation (eq. 66 and the formulae for σ_y and σ_{zp} described in MFD p59-62) unique to AERMOD or does it have another origin and how has it been evaluated?

Effect of turning off the penetrated plume.

run h2 is ~ identical to h1 (Zic calculation corrected as in v12345 – negligible difference);
run h3 is as per h2 but with the concentration contribution from the penetrated plume set to zero in the code;
the penetrated plume dominates the highest modelled concentrations at the Shotts monitoring site (8 km from the power station).



The following slides use debug output to examine these highest concentrations in h2 and h3, to demonstrate that these concentrations occur on different occasions when different phases of dispersion are dominant (plume penetration-fumigation c.f. plume trapping) and that the penetration-fumigation process that gave rise to the h2 maximum was very dominant, contributing much almost 90% of the total concentration for that hour at Shotts. AERMET records associated with the highest hours are included on the following slides.

Highest concentration in run h2, hour 98072309:

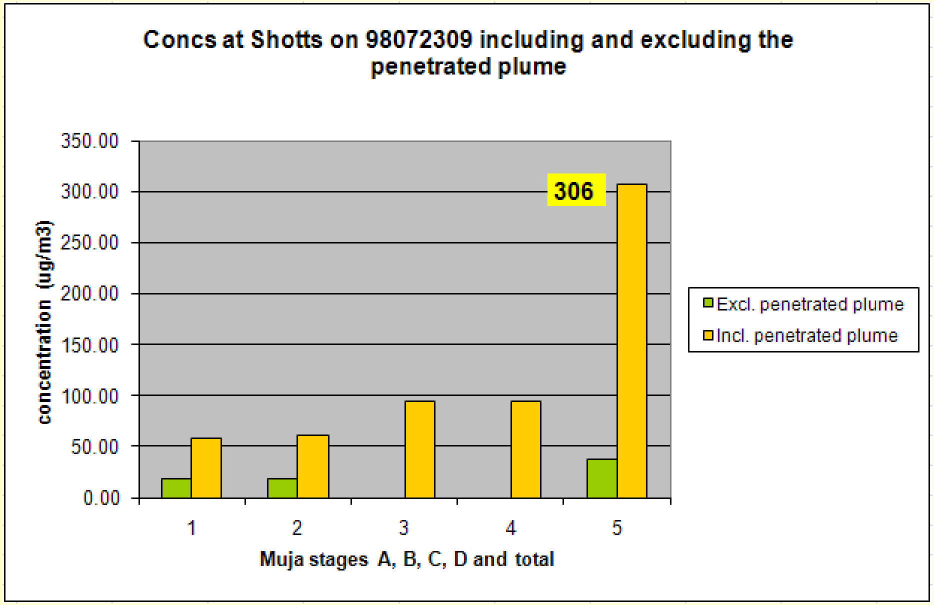
The first graph shows concentrations from each stage (stack) at Muja PS, including and excluding the contribution of the penetrated plume, and the totals from all stacks. The second graph shows plume components. Values were obtained from debug output.

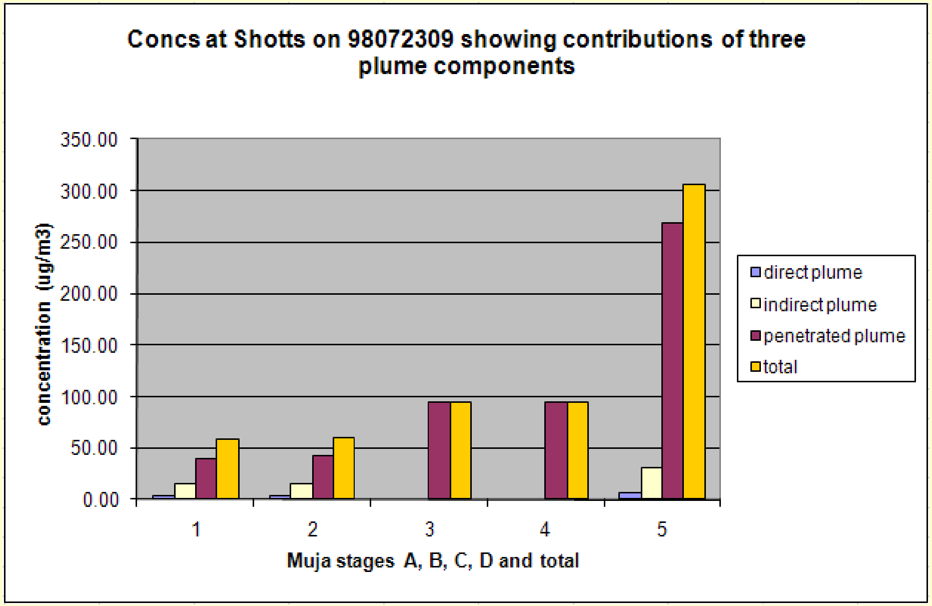
Only the smaller A & B plumes are not fully penetrated.

Penetrated plumes cause 88% of the total concentration at Shotts from Muja.

The contribution from the alumina refinery is negligible

yr	mo	dy	jd	hr	Hs	u*	w*	VPTG	Zic	Zim	L	z0	B0	r	Ws	Wd	Zref	Temp	Ztemp
98	7	23	204	9	18.7	0.221	0.369	0.011	96	239	-51.8	1	1	0.27	1.5	147	36	280.4	36





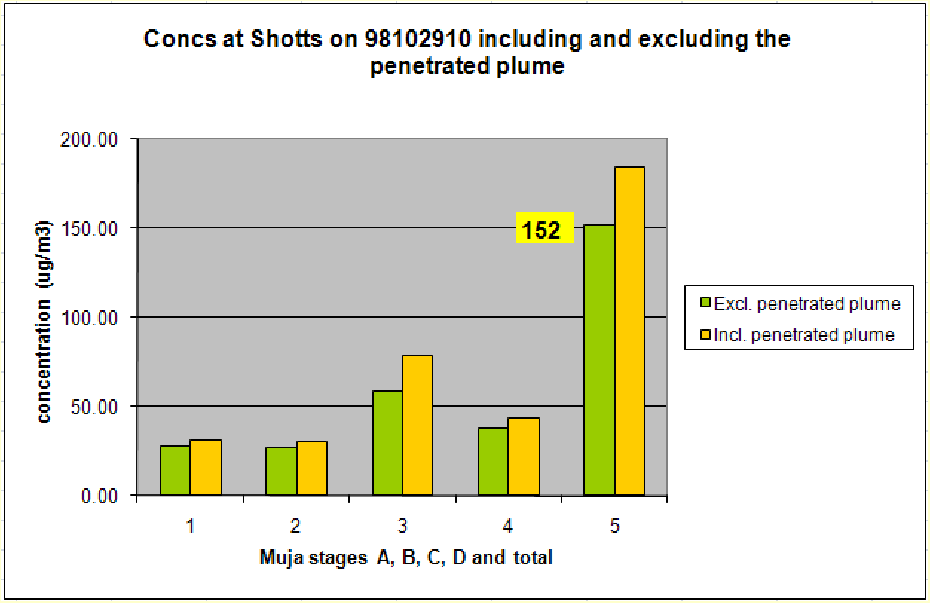
Highest concentration in run h3, hour 98102910:

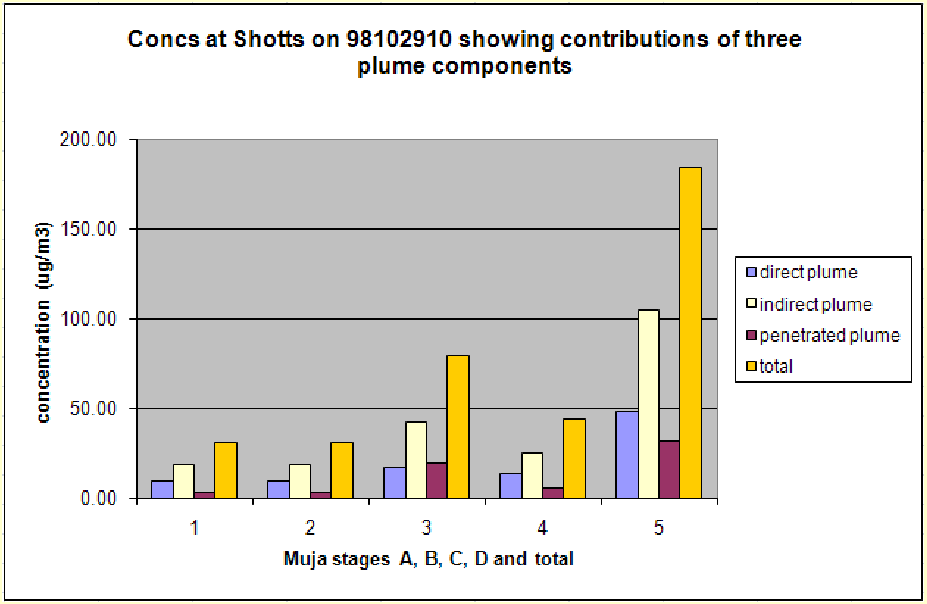
Compare to the foregoing graph for run h2 - penetrated plumes make a relatively minor contribution at Shotts for all Muja stacks, so that exclusion of the penetrated plumes reduces the total concentration by a relatively small amount, from 184 to 152 (152 is the value on the QQ plot for h3 above).

The indirect plume is the major component for each plume, due to a high fraction of trapping for all plumes within the 442m convective mixed layer.

The contribution from the alumina refinery is negligible.

yr	mo	dy	jd	hr	Hs	u*	w*	VPTG	Zic	Zim	L	z0	B0	r	Ws	Wd	Zref	Temp	Ztemp
98	10	29	302	10	55.4	0.291	0.882	0.01	442	361	-39.7	1	1	0.1	1.9	147	36	288.8	36





Penetration and dispersion - AERMOD's plume c.f. CALPUFF's puff

- NOTE – the following are Ken Rayner's observations – comments welcome.
- A plume penetrates and disperses within a 1-hour timestep. Dispersion of a penetrated puff may occur an hour or more later (an obvious point but it can make a big difference to concentrations).
- A partly trapped "indirect" plume disperses via a convective PDF formulation. A partly trapped puff does not (CALPUFF uses a Gaussian distribution in the vertical for this case).
- On the other hand, a penetrated plume disperses via a vertical Gaussian formula, not convective PDF. Because penetrated puffs typically have very small σ_z, they are typically fully entrained in a single timestep by a growing mixed layer, and dispersion of a fully entrained puff is via convective PDF, hence relatively rapid vertical dispersion, relatively large concentrations. *(And this could occur if the mixing height had been set to Zim, despite convective turbulence not being fully developed in the upper portion of Zim).*
- Note – comments on CALPUFF's behavior are based on other work provided to Bob Paine for review, available on request.

Aspects of AERMOD formulation that may warrant review.

- Slides 26, 27 show apparent AERMOD underestimation in well developed convective conditions at distances of 8 km and greater (tentative finding). Reasons considered to date:
  - Lateral dispersion formulation under unstable conditions;
  - Meandering plume.

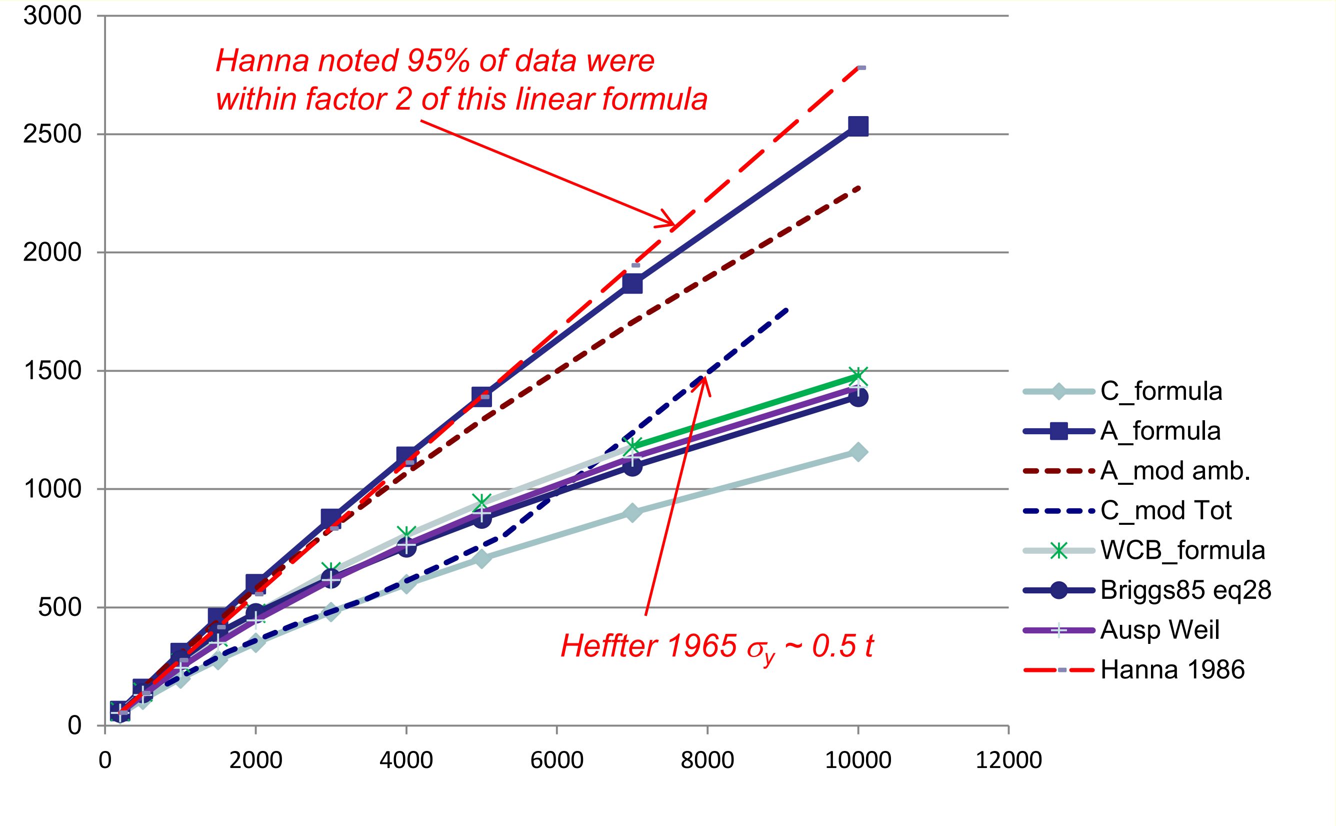
- Initial examination and questions in the following slides.

AERMOD lateral dispersion formulation c.f. others.

- See in the next slide a graph of various σ_y formulae for Muja A using AERMET results printed above the graph. Convection is developing in this mid-morning hour. See the spreadsheet *Sigma Y formulae.xls* for AERMET data and σ_y calculations.
- AERMOD and CALPUFF curves are calculated from tech. documents and also extracted from debug output. Agreement is quite close in each case (noting that guesstimates were made for height in CBL and u_{eff}).
- AERMOD σ_y is close to linear for a 100 m stack – much larger σ_y values than others (except a linear option noted by Hanna 1986). Has this difference been examined and confirmed, noting sensitivity of AERMOD's formula to source height? If based on field observations, how important was shear, topographic effects? What scales of motion are large enough to give near-linear growth far from the source? Is there any "double counting" of plume meander by the σ_y formula and the meandering plume formulation?
- The CALPUFF formulation, including Heffter (1965), is quite different to all others. The Heffter formula gives a fixed growth rate of 1.8 km per hour, irrespective of stability or anything else, after reaching a user-selectable handover value of σ_y. Is this reliable?

Various σ_y formulae – convective dispersion

AERMET data used to derive the σ_y curves:							
hour	u*	w*	Zic	Zim	L	z0	speed
10	0.279	1.483	1001	339	-16.6	0.25	2



C_formula: CALPUFF UG eq 2-65
A_formula: Aermod MFD
A_mod amb.: AERMOD debug σ_y ambient
C_mod Tot: CALPUFF debug σ_y + Heffter

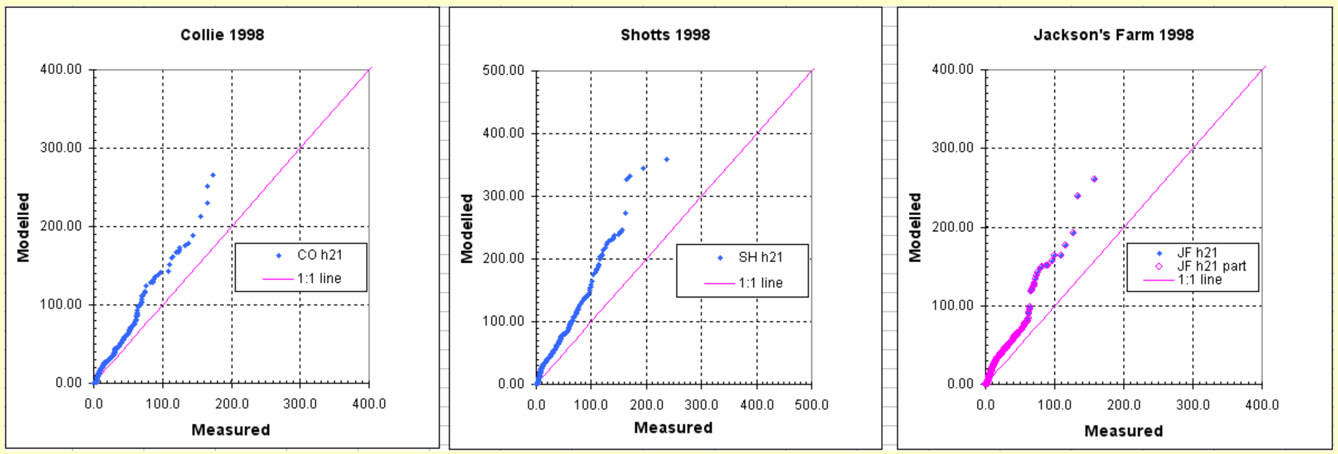
WCB_formula: Weil et al. 1997
Briggs85 eq28: J Clim & Appl Met p 1167
Ausplume Weil (not sure of ref.)
Hanna 1986: J Clim & Appl Met p1426

Forcing AERMOD and CALPUFF a little closer…..

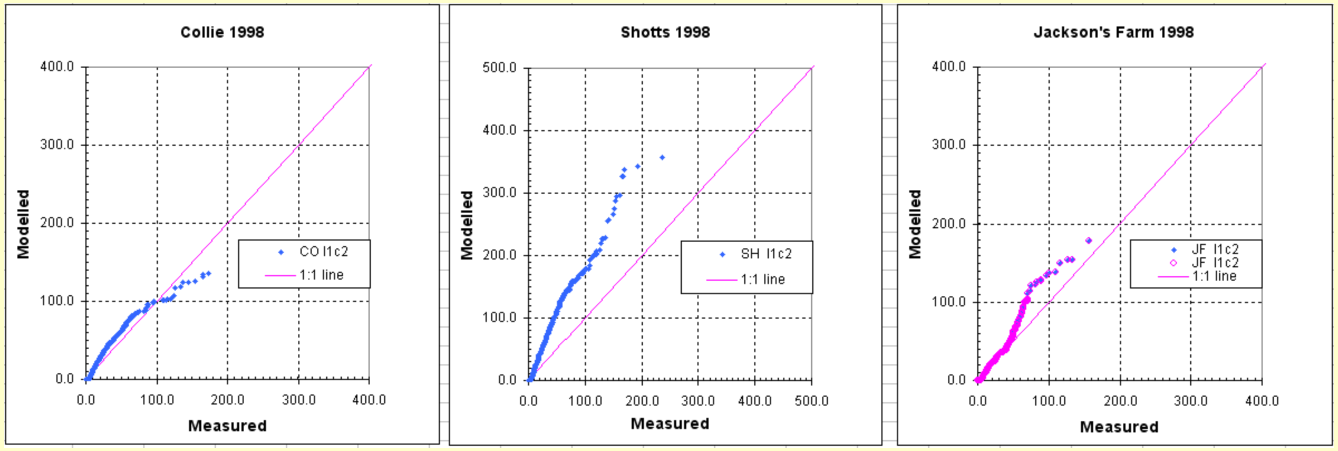
Interesting to note that disabling the meandering plume in AERMOD while making CALPUFF's σ_y linear from the source, like AERMOD, gives closer agreement at Shotts (closest monitor) while making CALPUFF values lower at more distant monitors.

Not suggesting that these model changes have merit!

AERMOD h1/h2 (slide 6) with meandering plume disabled



CALPUFF I1a1 (slide 8) with Heffter linear σ_y starting at source



Other AERMOD questions.

- AERMOD uses Zi = MAX(Zim, Zic) in unstable conditions. Zim is calculated from the formula of Venkatram (1980), which is valid if the temperature scale T_* is approximately constant in stable conditions. But T_* changes sign and magnitude from night to day (unstable) so how can the formula be validly used in unstable conditions? Should an alternative neutral-conditions formula be used?
- A smoothing formula is applied to Zim. It gives rapid growth but slower decline which can result in long post-sunrise transition periods while Zic catches up to Zim. Realistic?
- Isn't the fixed depth (500 metres) of the layer above Zic, over which the $d\theta/dz$ is calculated, sometimes excessive, e.g. after sunrise, Zic low and growing, plume penetration-dispersion dominant? The actual $d\theta/dz$ that determines plume leveling height could easily be greater than that over 500m for other than very buoyant plumes.

Other AERMOD questions cont....

- Most met parameters, measured or calculated, are hourly averages whereas Zic is an end-of-hour integrated value – this affects w* too. May cause under-estimation of concentrations – has this been considered?
- Modeling studies using TAPM indicates that plume enhancement from adjacent stacks may be significant for Muja power station. The Briggs 1975 plume enhancement method produces a 10 to 25% reduction in the predicted concentrations. Is there some standard practice for considering plume enhancement from adjacent stacks in the US?
- Appropriate model performance measures? (For a few far-flung monitoring stations, QQ plots and residual plot analyses seem appropriate.)
- Comments on important meteorological measurement welcome, e.g. wind and temperature profiles (RASS Sodar?), turbulence – what parameters and heights?

Evaluation of AERMOD SO_2 Predictions for a Research-Grade Field Experiment

Paper # MO10
Presented at the
Guideline on Air Quality Models: Planning Ahead
March 19-21, 2019
Durham, NC

Jeff Connors, Christopher Warren, and Robert Paine
AECOM, 250 Apollo Drive, Chelmsford, MA 01453

ABSTRACT

The Collie region in Western Australia has a number of significant sources of atmospheric emissions associated with mining, electricity generation and alumina refining. The major sources of air pollution include 3 coal-fired power plants and an alumina refinery. Due to the extent of the emission sources in the area, the Western Australia Department of Environmental Conservation (WA DEC) has overseen ambient measurement studies and air dispersion modeling studies for this area. The need for a Collie Airshed Study (CAS) has been addressed by the installation of a comprehensive network of 12 SO_2 monitoring stations, several meteorological measurements, and collection of hourly emissions information.

This paper reports on the results of an AERMOD[1] model evaluation study involving the initial 6 months of a 2-year model evaluation study. Due to the relatively flat terrain and tall stacks for the major sources, the peak concentrations are observed to occur during convective conditions, especially on low wind speed days in the summer. The evaluation exercise involves a number of AERMOD variations in order to determine the best performing model, including options with the ALPHA LOWWIND keyword exercised. The results of the evaluation have been used to recommend enhancements in the ongoing measurement program as well as additional areas of model review.

INTRODUCTION

The Collie region has a number of significant sources of atmospheric emissions (SO_2) associated with mining, electricity generation and alumina refining. The major sources of air emissions include:

- Muja Power Station,
- Collie Power Station,
- Bluewaters Power Station, and
- Worsley Alumina Refinery.

Due to the extent of the emission sources in the area, the Western Australia Department of Environmental Conservation (WA DEC) has overseen several ambient measurement and air dispersion modeling studies for this area.

The industrialized sources in the Collie Region have generally accepted the merits of developing an airshed management strategy, supported by reliable modeling and adequate monitoring. Despite the existence in the past of a significant monitoring program (1996-2001), the WA DEC requires a comprehensive, integrated monitoring program to be undertaken to demonstrate the reliability of a model (or models), in light of:

- limitations in the previous monitoring program;
- major emissions sources added since the previous monitoring study concluded (2001),
- the potential for higher sulfur content in coal to be used by the plants in the future, creating the potential for ambient SO_2 criteria to be approached;
- lack of reliable data on actual emissions for all sources for model input; and
- WA DEC's preference that any airshed management strategy be based on a model proven to be reliable using comprehensive and reliable data on emissions, ambient concentrations and meteorology.

COLLIE AIRSHED STUDY OVERVIEW

The need for the Collie Airshed Study (CAS) has been addressed by the installation of a comprehensive network of SO_2 monitoring stations, meteorological measurements, and collection of hourly emissions information. Figure 1 shows the entire region for the emission sources and the monitoring network, consisting of 12 SO_2 monitoring stations.

Additional model evaluation exercises for the CAS will be conducted once a more complete database is available. The focus of this initial model validation exercise, utilizing the initial 6 months of data, is to meet the following objectives:

1. To evaluate the performance of the preferred model (AERMOD) in predicting ground-level concentrations at the monitoring sites.
2. To determine if any potential improvements can be made to the measurement program or to the dispersion model for the remaining period of the monitoring study.

To carry out these objectives, a basic evaluation of the meteorological data was performed followed by the actual model evaluation.

The meteorological data evaluation involved a preliminary evaluation of the 6 months of meteorological data collected early in the program (November 2017 – April 2018) to evaluate the quality of the data and assess the performance of the meteorological pre-processor to AERMOD, AERMET.

A review of the emissions, meteorological, and monitoring data indicates a database with a high data capture that is very useful for the initial model evaluation study. The monitoring data indicates that, as expected, most of the peak SO_2 concentrations occur during the daytime hours (with the majority occurring during the late morning to early afternoon). This understanding helped to focus the review of the meteorological conditions upon daytime hours and the growth of the convective mixing layer.

A considerable effort was made to review data from the various meteorological towers and Sound Detection and Ranging (SODAR) instruments to determine the best set of meteorological data to be used for input into AERMOD. The data capture and detection range from the main Scintec SODAR and Radio Acoustic Sounding System (RASS; collocated with the 80-m tall meteorological tower) were low during the six months reviewed for this study due to site-specific issues. With the installation of additional acoustic material at the base of the SODAR, there has been a significant improvement (at least 90% data capture) in the performance of that instrument since May 2018.

The importance of the daytime hours guided the meteorological analysis toward a review and evaluation of the heat flux and soil measurements and use of that information to determine the allocation of net radiation toward the major components of sensible and latent heat flux. The growth of the convective boundary layer predicted by AERMET was tested during a period of multiple radiosonde launches that occurred from March 6-15, 2018. This testing is described in detail in a companion paper[2] and will not be repeated here.

The actual model evaluation evaluated AERMOD's predicted ground-level concentrations for each monitoring site by modeling all of the major sources listed above. The evaluation was conducted for two heat flux approaches; a Base and Alternative Case, along with variations in the turbulence data used as well as "LOWWIND" options (minimum sigma-v values) available in AERMOD. A screening evaluation utilizing several model options was used to narrow the list of best performing models for a larger set of statistical tests.

AERMOD's predicted ground-level concentrations at each of the 12 monitoring sites was evaluated by modeling all sources (i.e., no discrimination by source). The evaluation was conducted for the following 6 cases, as requested by WA DEC:

- All observations;
- Convective mixing height < 600 meters;
- Convective mixing height > 900 meters;
- Convective velocity scale < 1 m/s;
- Convective velocity scale > and = 1 m/s; and
- For hours between 11 and 17 WST with the ambient temperature greater than 20°C.

For each of the above listed cases, several statistical analysis techniques were used for these evaluations, including quantile-quantile ("Q-Q") plots and statistical measures such as the European Environmental Agency Relative Mean Error and the Robust Highest Concentration, meteorological conditions for the top 5 1-hour concentrations at each monitor, and residual plots of concentration versus distance.

FIELD STUDY MEASUREMENT PROGRAM

The CAS includes four major SO_2 emission facilities consisting of eight stacks; the Muja Power Station (2 stacks), Collie Power Station (1 stack), Bluewaters Power Station (2 stacks) and Worsley Alumina (3 stacks). Table 1 lists the stack parameters with the location of the sources. One of the stacks from the Worsley Alumina facility has 3 separate flues contained within a single stack. Hourly SO_2 emissions were tracked using continuous emission monitoring systems (CEMS) for all sources during the 6-month initial study period with the exception of the Worsley Alumina Boilers 1-3. Temporary CEMS were installed in February 2018 for Worsley Alumina sources. Prior to that step, parametric monitoring was used to estimate the emissions for these boilers. Figure 2 provides hourly time-series plots for all sources to be modeled as part of the study.

Figure 1: Collie Airshed SO_2 Sources, Monitoring Network and Meteorological Sites

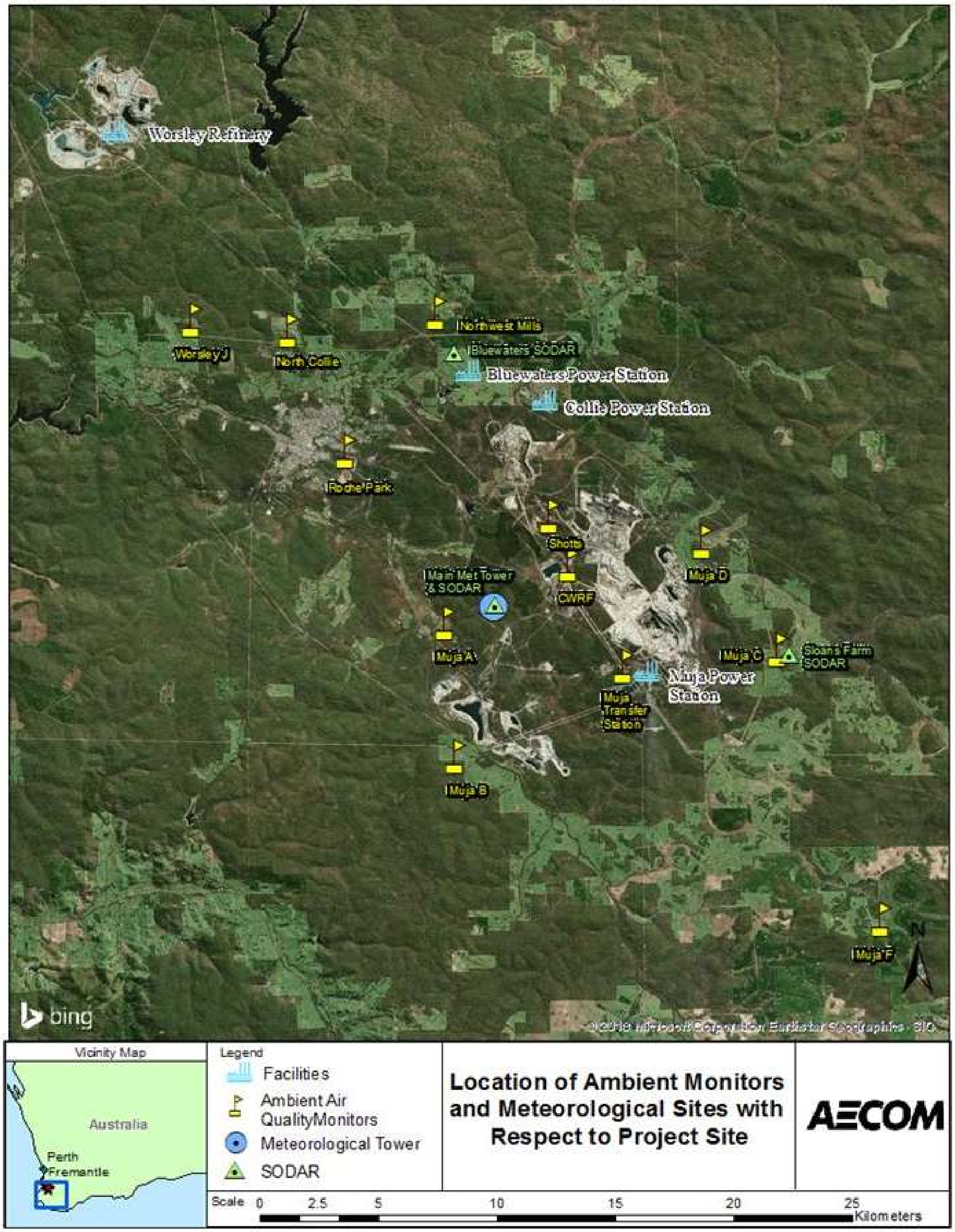


Table 1: SO_2 Source Locations and Stack Parameters

Source	Easting (m) MGA94	Northing (m) MGA94	Stack Height (m)	Stack Diameter (m)
Muja Unit C	435636	6299074	151	5.91
Muja Unit D	435525	6299109	151	5.91
Collie Unit A	431227	6310439	170	5.23
Bluewaters Unit 1	428126	6311651	100	4.00
Bluewaters Unit 2	428202	6311609	100	4.00
Worsley Boilers 1-3	413242	6322257	76	2.30
Worsley MFC 5	412750	6322140	90	2.50
Worsley MFC 6	412750	6322074	90	2.50

The "raw" SO_2 monitoring data were 5-minute average values; 1-hour averages were computed from this information. Applicable SO_2 ambient standards[3] for Australia are: a 1-hour standard of 200 ppb (can be exceeded on only 1 day per year), a daily standard of 80 ppb (can be exceeded on only 1 day per year), and an annual standard of 20 ppb. A summary of the maximum 1-hour SO_2 value for each month and over the entire 6-month study period is plotted in Figure 3. The highest hourly SO_2 observed concentrations generally occurred during the summer months of January through March.

The design of the meteorological monitoring program for the CAS had the goal of providing a vertical profile of several levels of wind, temperature, and turbulence data for input to dispersion models such as AERMOD. In addition, with the expectation that the daytime hours with convective mixing would be very important in the modeling analysis, measurements of heat flux components were included in the measurement program.

AERMOD uses measured or parametrized estimates of horizontal and vertical atmospheric turbulence to estimate plume spreading rates. These turbulence parameters are typically measured from the standard deviation of the crosswind wind speed in the horizontal, or σ_v, and the standard deviation of the wind speed in the vertical, or σ_w. In the absence of observed turbulence measurements, AERMOD will parameterize these variables. In general, we would expect the AERMOD model performance to be optimized with the use of the measured turbulence data, but there are some applications where this is not necessarily the case. Therefore, for the model evaluation study, we conducted modeling tests with the turbulence data omitted for the initial modeling runs of the base and alternative meteorological dataset cases, and then included turbulence data for subsequent modeling runs.

Table 2 summarizes the recommended meteorological data from the November 1, 2017 – April 30, 2018 period selected for use in the model evaluation of the Collie Airshed Study.

Figure 2: Hourly Emission Time Series for Major SO_2 Sources within the Collie Airshed (November 2017 – April 2018)

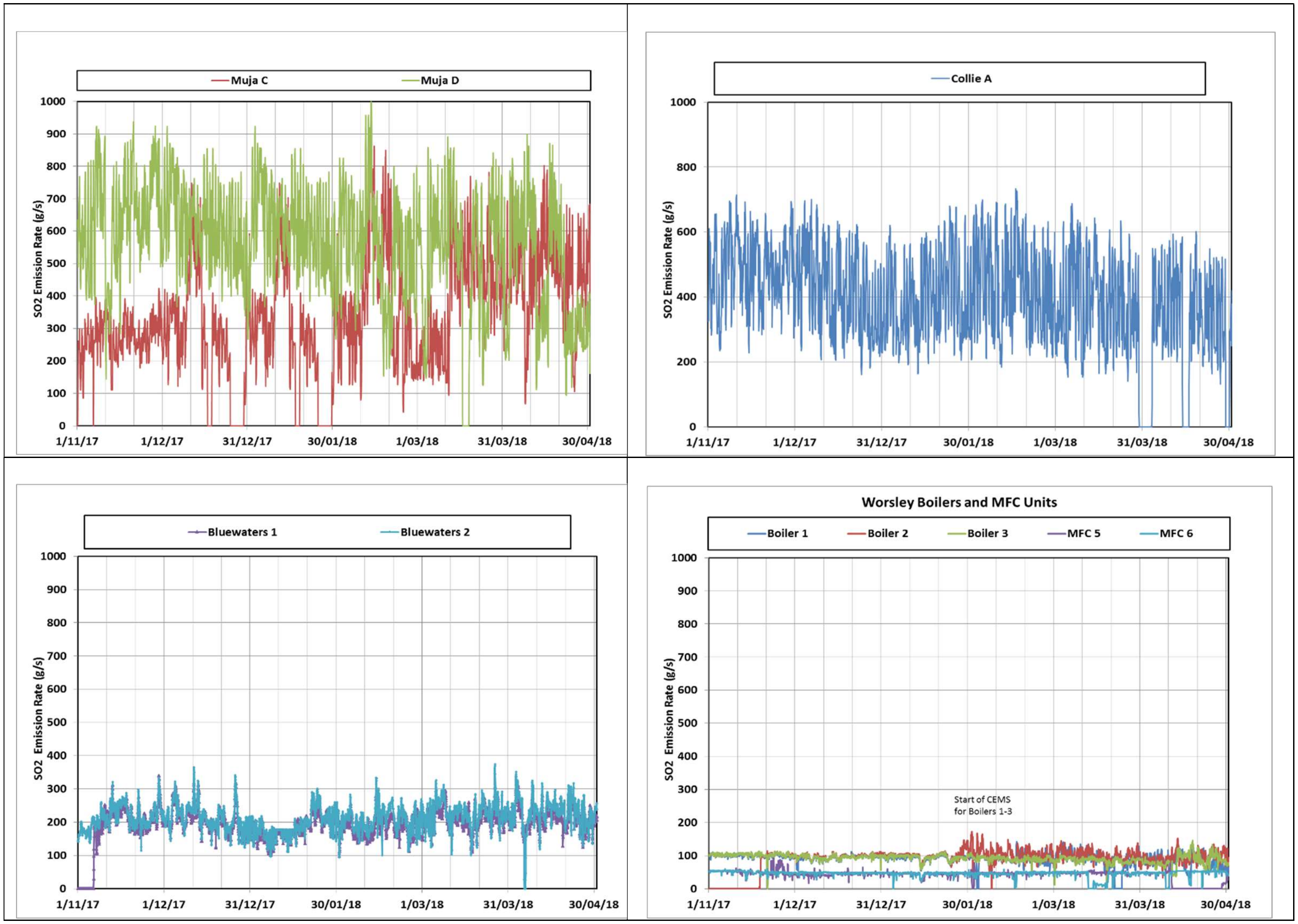


Figure 3: Monthly Distribution of the Maximum Hourly SO_2 Ambient Measurements November 2017 to April 2018

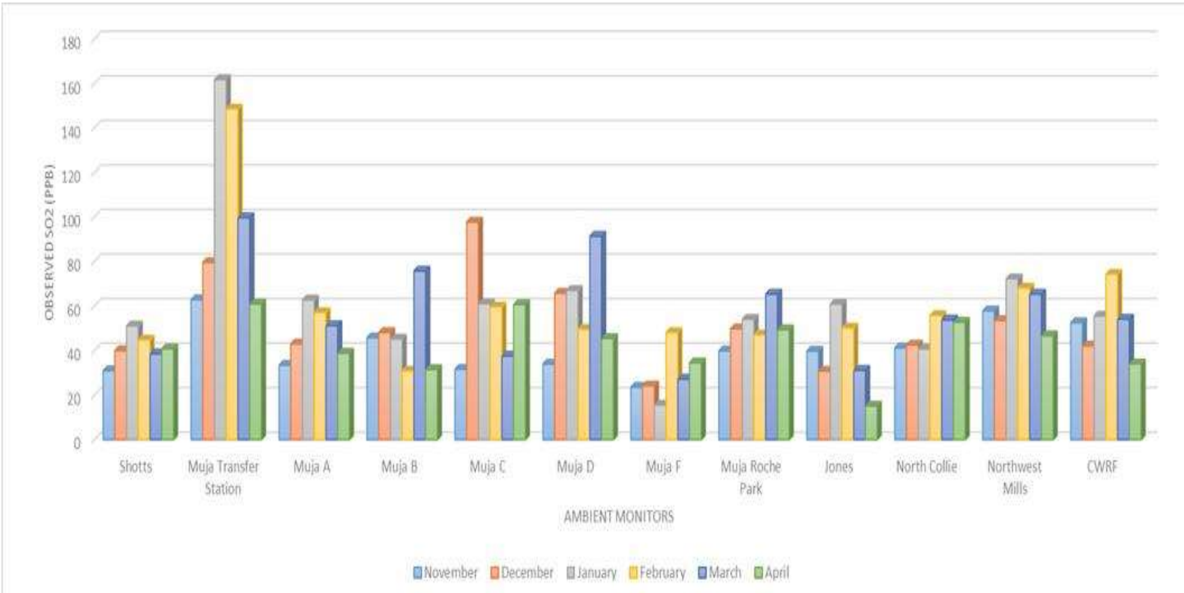


Table 2: Meteorological Data Supplied to AERMET for CAS Model Evaluation

Measurement	Height Above Ground (m)
Wind Speed	30, 50, 80
Wind Direction	30, 50, 80
Vertical Winds	30, 80
Ambient Temperature	2, 10, 30, 50, 80
Relative Humidity	2
Pressure	2
Net Radiation	80
Precipitation	2
Ceilometer	0 to 7,600
Eddy Covariance	35
Bluewaters SODAR (Wind Speed, Direction)	100 to 300 (10-m intervals)
Surface Roughness	1.08[1]
Bowen Ratio	Varies[2]
Upper-Air Radiosonde	On-Site (Perth used Nov 1-5, 2017)

1 Composite roughness length based on average of twelve 30° sectors around the Consortium tall tower.
2 Daily and Monthly average Bowen ratios used.

MODEL EVALUATION RESULTS

The initial phase of the modeling evaluation considered several candidate AERMOD approaches with limited statistical tests to determine the best candidates for more extensive testing and evaluation. The first set of modeling runs assessed the model performance between the two meteorological datasets. The primary difference between the two datasets is that the Base Case uses an approach that derives sensible heat flux values from daily-varying Bowen ratios, while the Alternative Case forces the predicted sensible heat flux in convective conditions to be equal to the measured flux data. All observational hours over the duration of the 6-month initial study period were included as part of this initial evaluation phase.

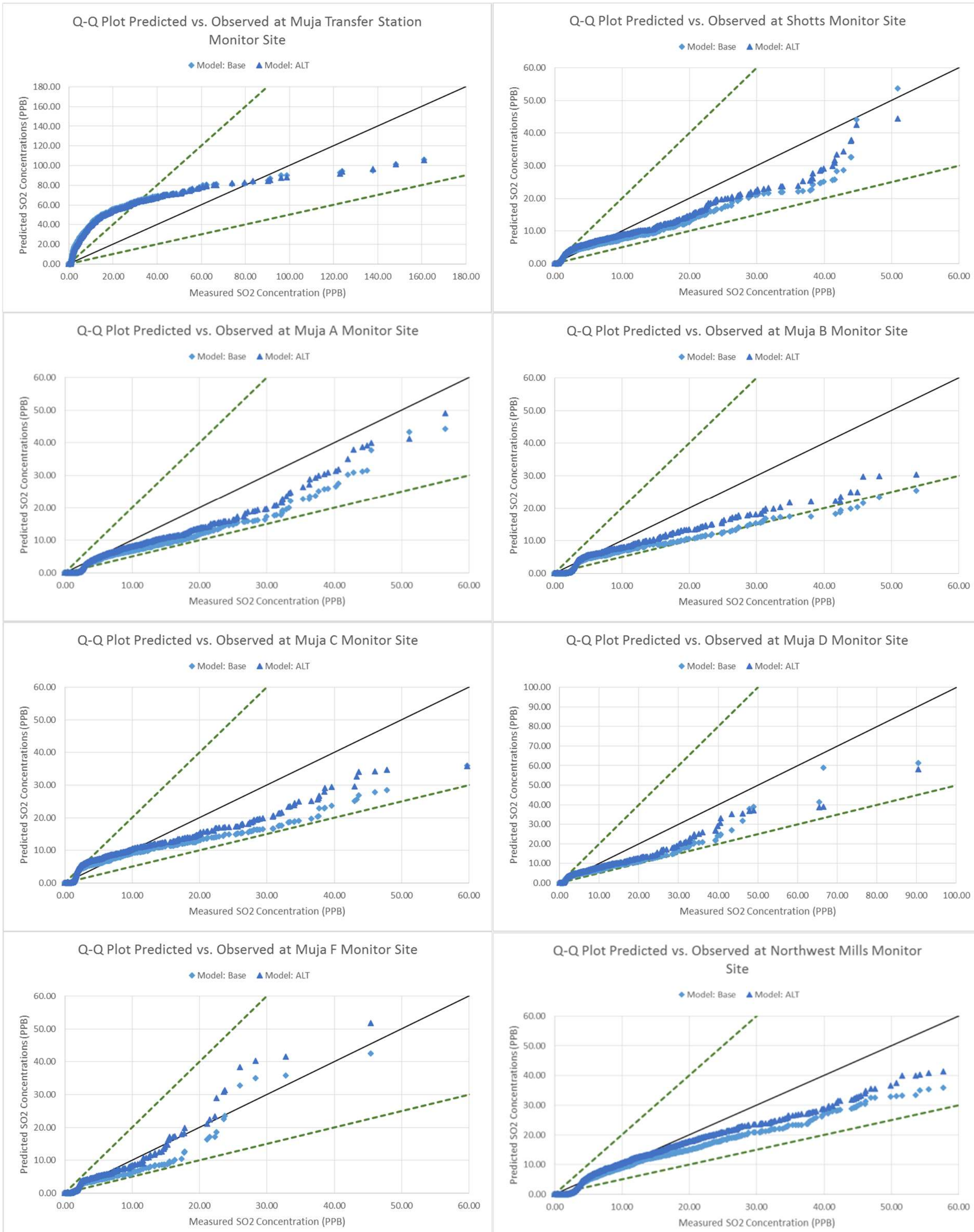
In general, the difference between the ranked hourly predicted concentrations between the Base and Alternative Case runs without turbulence were less than 20%. Overall, the Base Case runs demonstrated better performance than the Alternative Case. Q-Q plots for each of the monitor locations are provided in Figure 4 for modeling runs without turbulence data.

When the ranked-paired concentrations did exhibit larger differences (i.e., greater than 20%), the Base Case showed improved performance to the observed data over the Alternative Case dataset. The outliers consisted of Muja D and CWRF sites where a few ranked pairs differed by as much as 50%. For example, at CWRF, the highest ranked concentration for the Base Case run was 81.2 $\mu g/m^3$, while it was only 54.1 $\mu g/m^3$ for the Alternative Case. With the highest observed hourly concentration reported at CWRF being 73.8 $\mu g/m^3$, this is the difference between the Base Case model slightly over-predicting versus the Alternative Case model under-predicting.

One notable difference was seen at the Muja F monitoring site location (representing a relatively large distance between the source and monitor) where the Alternative Case dataset shows an over-prediction by the model for the highest predicted versus observed concentration, compared to an under-prediction by the model from the Base Case. Further review revealed that in both of the models' peak-predicted concentration events, the key plume component was from the penetrated plume (that is, the plume initially rose to a level above the convective mixing height). It is noteworthy that some AERMOD peak predictions can occur with the penetrated plume component, while others occur due to a direct plume component in which the plume is emitted within the convective boundary layer. For inversion breakup conditions, the time difference between these two types of events can be as short as a single hour.

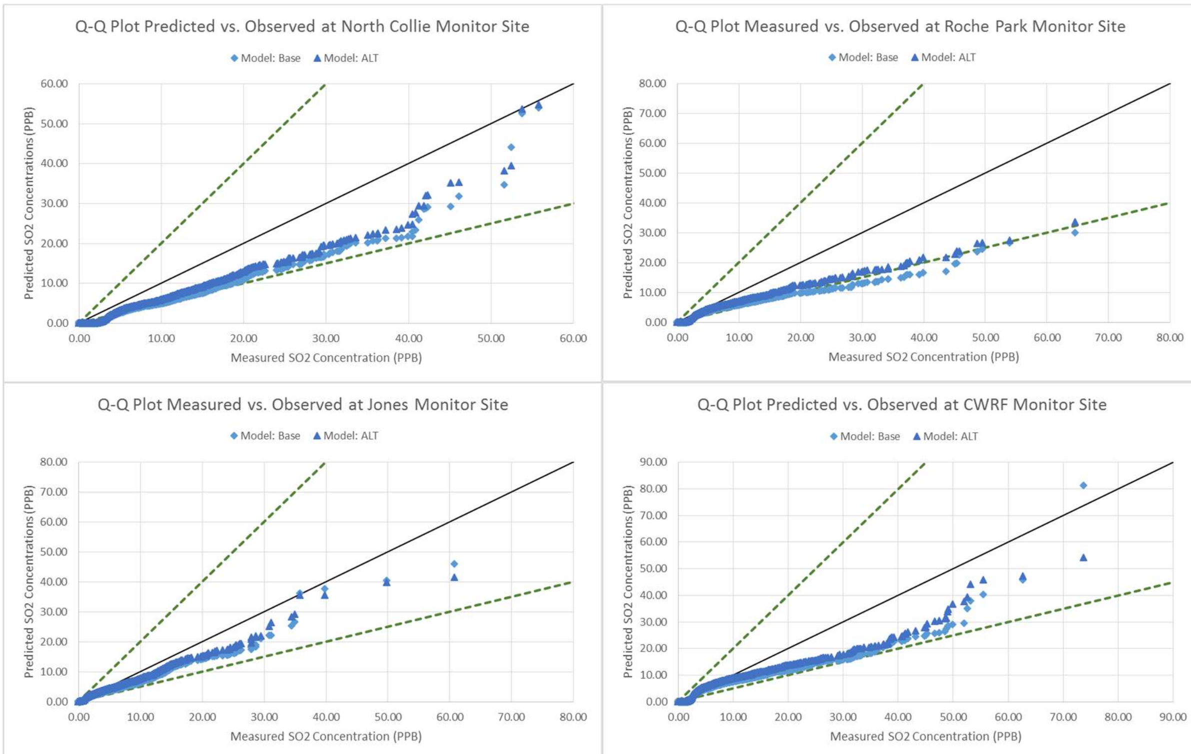
A key monitor is the Muja Transfer Station, which is only about 1 km from the Muja Station. At that monitor, the peak observations may be under-predicted due to stagnation events associated with inversion breakup conditions at mid-day. For these events, multiple hours of emissions can accumulate, and AERMOD has no memory of previous hours' emissions. The over-predictions for a large portion of the ranked concentration distribution is likely due to the plume penetration formulation, which results in plumes mixing to the ground too quickly in most cases (when the mixing height is still below the plume level). This issue is likely due to AERMOD's omission of a stable component of the sigma-w formulation, leading to values of sigma-w that are too high in most cases. The recommended correction is to test within AERMOD for cases where the mixing height would intercept the plume within the hour, and then allow for the high sigma-w values only then.

Figure 4: Q-Q Plots for No Turbulence Base and Alternative Case Runs



Note: Dashed lines represent 1-to-2 and 2-to-1 measure-to-predicted ratios.

Figure 4: Q-Q Plots for No Turbulence Base and Alternative Case Runs, continued



Note: Dashed lines represent 1-to-2 and 2-to-1 measure-to-predicted ratios.

At several of the monitors, a model under-prediction tendency is noted. These monitors range from about 5-10 km from one or more sources. Therefore, this issue will be further investigated with a full grid of receptors, as well as sensitivity testing for the roughness length used (currently about 1 meter). Due to the fact that only a 6-month period has been tested, the model evaluation will be extended to a longer period in a planned effort for the future. Other means of determining possible causes of AERMOD under-prediction will be the use of model sensitivity plots with the predicted-to-observed ratio plotted on the y-axis versus a variable such as mixing height, wind speed, etc.

Additional model performance evaluations were conducted prior to the selection of a "best model performing dataset" for the Collie Airshed, including the following model options:

- Inclusion of sigma-theta component of turbulence data,
- inclusion of sigma-theta and sigma-w components of turbulence data, and
- use of AERMOD's LOWWIND alpha option.

The Robust Highest Concentration (RHC)[4] was computed for several modeling options at each monitor; the results are plotted in Figure 5. The runs that include sigma-w nearly always show ratios well below 1.0 (under-predictions). The only exception is at CWRF, where the ratios for the sigma-w options are comparable to the other runs. It should be noted that sigma-theta and sigma-w inputs to the model were only obtained from the 80-m tall tower. Given the recent improvements in SODAR data returns, future work is anticipated to involve assessing the use of the turbulence data from this instrument. Otherwise, the options using sigma-theta and sigma-theta with LOW_WIND perform the best overall.

Figure 5: Ratio of the Robust Highest Concentration (RHC) for N=10 for Sigma-theta and Sigma-theta with LOW_WIND Runs at Each Monitoring Site

Low RHC ratios are seen at three specific monitors: Muja B, Muja C and Roche Park, indicating the model is under-predicting at those monitors by more than 30%. Under-predictions at three other monitors range between 10 and 30%, while predictions at two monitors are within 10% of being unbiased. Four monitors have over-predictions of more than 10%. The overall model performance over the monitors other than the three with the largest under-predictions with the use of sigma-theta and sigma-theta with the LOWWIND option is encouraging, with a geometric mean predicted-to-observed RHC ratio of 1.02 for the sigma-theta option and 0.97 for the sigma-theta with LOWWIND option for the Base Case modeling runs.

Although the extent of the monitors deployed (12 in total) is quite extensive, the concentration pattern over the entire area has not yet been reviewed. It is also unclear by just modeling at these discrete locations whether the plume predicted by the model is directly impacting these locations, partially hitting or completely missing. While a model run using a nested receptor grid that would cover the entire Airshed domain (i.e., 40 km by 40 km) would likely provide valuable insight into this uncertainty, a review of whether the model is performing well at various distances based on the data points currently being used is a useful evaluation test.

Figures 6, 7, and 8 show the maximum, 5th and 10th highest concentrations for observed and predicted (Base and Alternative Cases without turbulence) for monitors grouped by distances from the Muja Power Station. The near-field distance group is represented by the Muja Transfer Station monitor, which is located approximately 1 km from the station. The intermediate distance group consists of monitors located between 5 and 9 km from Muja and include; Muja A, B, C, D and CWRF. The far-field distance group includes Muja F, located approximately 14 km to the southwest of Muja. These monitors were selected as the dominant SO_2 source is the Muja Power Station, which allows for a "cleaner" evaluation rather than needing to account for multiple sources as varying distances.

One important finding from this distance-from-source analysis is, as expected, that the concentration decreases as the distance from the source increases for both monitored and predicted concentrations. A second finding is that the analysis suggests that AERMOD is under-predicting at closer distances from the source and trending to over-prediction at the far-field (i.e., Muja F). This is the case for the maximum and 5th highest values, but for the 10th highest value, the model and observations in the near-field appear to be almost identical. AERMOD under-predictions at the closer distances need further attention, with some future sensitivity analyses planned for roughness length variations and the meander fraction used in AERMOD.

An additional finding is that when the monitors around Muja Power Station are grouped by distance and the ratio of the predicted-to-observed RHC is calculated, the result suggests that AERMOD handles the concentrations in the intermediate range relatively well, within about 20-25%, as shown in Table 3. Figure 9 illustrates this using a scatter plot. These percentages fall within the typical mean biases of air quality models (20 to 40%) as suggested by Hanna[5].

SUMMARY AND CONCLUSIONS

AECOM has conducted a preliminary review of 6 months of meteorological, emissions, and SO_2 monitoring data in order to develop a reliable site-specific dispersion model for the Collie Airshed in Western Australia. This preliminary study provides an assessment of a candidate dispersion model, AERMOD, for use in the Collie Airshed management.

Two meteorological datasets (Base and an Alternative Case) were prepared and evaluated using AERMOD on the 6-months of Collie Airshed data. The Base Case estimated the sensible heat flux and convective mixing height through the use of measured net radiation, daily-averaged Bowen ratios (derived from measured sensible and latent heat flux data), and cloud cover data. The Alternative Case used AERMET to predict the measured sensible heat flux by modifying the input of net radiation and holding the Bowen ratio constant. In both cases, the initial modeling runs excluded the use of turbulence data. The results of this initial modeling indicated that the Base Case meteorological dataset appeared to perform slightly better than the Alternative Case. Further evaluations included testing these datasets with available turbulence data from the tall tower and using AERMOD's low wind option ("LOW_WIND"). Two clear frontrunners emerged based on these analyses, the sigma-theta and sigma-theta using LOW_WIND from the Base Case meteorological dataset.

Figure 6: Maximum 1-hour Model Concentrations vs. Distance from Muja Power Station

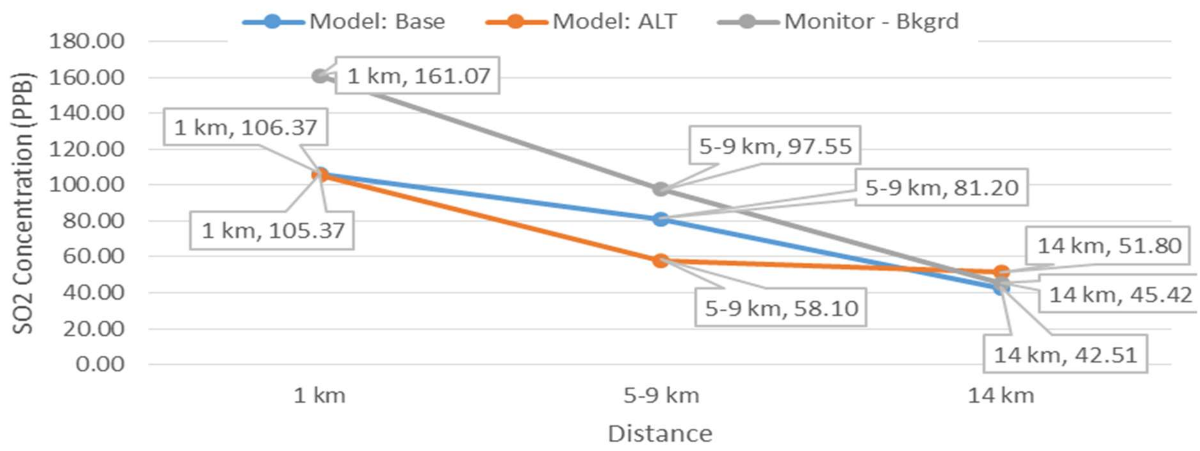


Figure 7: 5th Highest 1-hour Model Concentrations vs. Distance from Muja Power Station

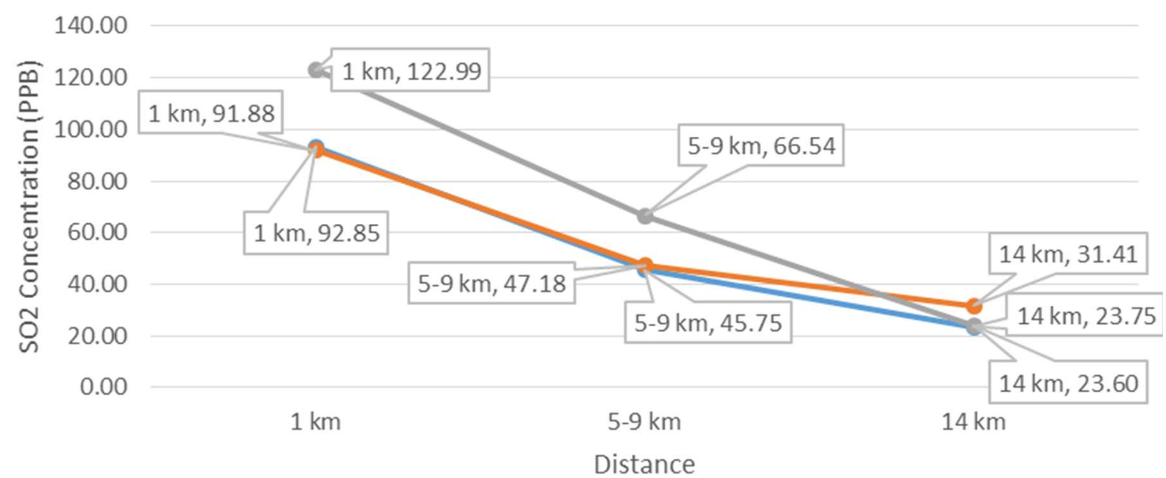


Figure 8: 10th Highest 1-hour Model Concentrations Compared to Distance from Muja Power Station

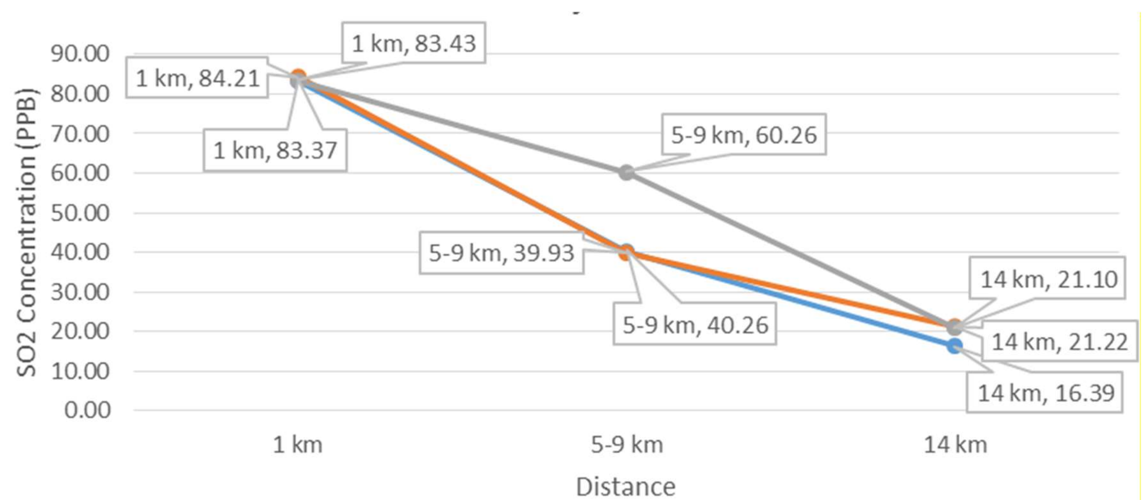
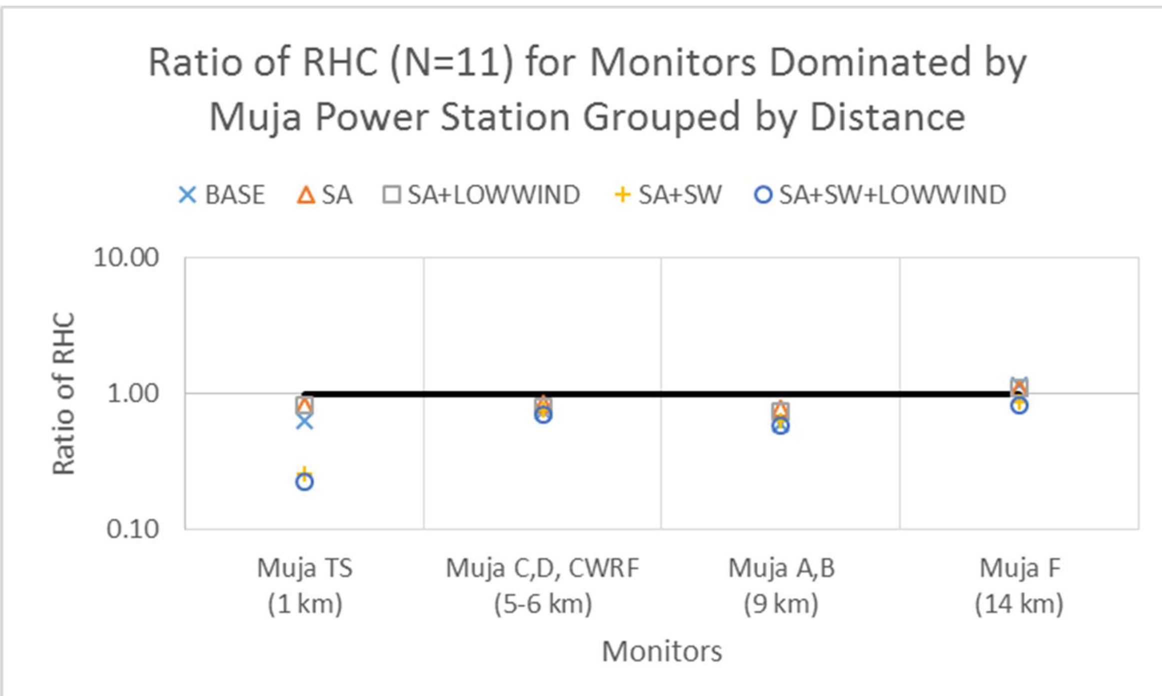


Table 3: Ratio of the Robust Highest Concentration (RHC) for N=10 Using Base Case Meteorological Dataset by Monitors Grouped by Distance from Muja Power Station

Model Run	Muja TS (1 km)	Muja C,D, CWRF (5-6 km)	Muja A,B (9 km)	Muja F (14 km)
BASE	0.63	0.74	0.60	1.17
SA	0.82	0.85	0.78	1.12
SA+LOWWIND	0.82	0.80	0.74	1.10
SA+SW	0.26	0.76	0.64	0.86
SA+SW+LOWWIND	0.23	0.71	0.59	0.82

Notes: OBS = observations, BASE = Base Case without turbulence, SA = sigma-theta, SA+LOW_WIND = sigma-theta with LOW_WIND option, SA+SW = sigma-theta and sigma-w, SA+SW+LOW_WIND = sigma-theta and sigma-w with LOW_WIND option.

Figure 9: Ratio of the Robust Highest Concentration (RHC) for N=10 Using Base Case Meteorological Dataset by Monitors Grouped by Distance from Muja Power Station



One area that appears to be a consistent feature from earlier AERMOD evaluations is that the peak concentrations predicted by AERMOD occur earlier in the daytime period than the peak observed concentrations (also in the daytime). This is due, in part, to AERMOD's "anticipation" that the plume that rises into the stable layer above the convective boundary layer (the "penetrated plume") eventually mixes down to the ground, but AERMOD predicts this to happen earlier than it actually does. The observed peak concentrations are delayed until the time (in an event typically lasting about an hour) when the convective mixing layer actually intercepts the penetrated plume and mixes it to the ground.

More work is needed to fully diagnose and correct this AERMOD model behavio, but one area of scrutiny is the parameterization of the penetrated plume vertical spreading (sigma-z). Note that AERMOD simulates three plume components in convective conditions: the "direct" plume that reaches the ground in a convective downdraft, the "indirect" plume that reaches the top of the boundary layer in a convective updated, and the "penetrated plume" that has sufficient buoyancy to reach the stable layer aloft (or gets directly injected into that layer if the stack height is higher than the convective mixing height). AERMOD's formulation computes a vertically-integrated value of parameters such as sigma-w between the plume centerline and the receptor at the ground, even for the penetrated plume component. However, this calculation will substantially overstate the vertical plume growth if the actual plume behavior shows it not escaping from the stable layer aloft (and this has been observed in Bull Run lidar data[6]), while AERMOD presumes that the plume spreads to the ground. Once the vertical integration involves a significant depth within the convective boundary layer, the plume spreading will be greatly exaggerated due to the large turbulent eddies in the convective boundary layer. The plume spreading for the penetrated plume all the way to the ground is only appropriate for the hour when the convective mixing height rises to overtake the plume. Otherwise, the computation of the effective turbulence values for the penetrated plume should be limited to a layer that is smaller, such as to the top of the convective mixed layer until that layer rises to overtake the plume and mix it to the ground. This altered treatment would mix the penetrated plume all the way to the ground just for the hour during which the convective mixing height starts below the plume level and then rises to a level above it for the next hour.

Treatment of the penetrated plume issue is currently a "second tier" area for AERMOD development. It should be elevated to a first-tier status and be given a higher priority for being addressed.

There are a few caveats and limitations with the dataset tested so far:

- Only 6 months of data have been tested, with limitations in SODAR data and the inability to utilize the Scintec SODAR and RASS dataset;
- the maximum detection range for the SODAR and RASS instruments are nearly always too low (SODAR range 600-800 meters) to capture the top of the boundary layer (typically 800-1,200 meters from balloon launch data) (even with recent improvements at the Consortium SODAR site);
- the evolution of the inversion breakup and effects on plume transport (including fumigation) are not well captured with current upper-air data collection (i.e., a single near sunrise weather balloon launch), and the AERMOD model treatment needs improvement;
- AERMOD under-predictions at the intermediate distances need further attention, with some sensitivity analyses planned for roughness length length variations and the meander fraction used in the model.

ACKNOWLEDGEMENTS

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ATTACHMENT 2

MODELING PROTOCOL FOR ALTERNATIVE MODEL APPROVAL DEMONSTRATION FOR THE RUSK-PANOLA ATTAINMENT DEMONSTRATION STATE IMPLEMENTATION PLAN REVISION FOR THE 2010 SULFUR DIOXIDE (SO_2) NATIONAL AMBIENT AIR QUALITY STANDARD

ENVIRONMENT
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MODELING PROTOCOL FOR ALTERNATIVE MODEL APPROVAL DEMONSTRATION FOR THE ATTAINMENT DEMONSTRATION STATE IMPLEMENTATION PLAN REVISION FOR THE 2010 SULFUR DIOXIDE (SO2) NATIONAL AMBIENT AIR QUALITY STANDARD

PREPARED UNDER A CONTRACT FROM THE
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CONTENTS

1. Introduction

Portions of Rusk and Panola Counties in Texas have been designated as a nonattainment area[1] (NAA) for the 2010 sulfur dioxide (SO_2) National Ambient Air Quality Standard (NAAQS). The Martin Lake Electric Plant (referred to as Martin Lake Generating Facility), owned and operated by Vistra Energy Corporation (referred to as Vistra), is the primary source of SO_2 emissions in the Rusk-Panola NAA.

Initial dispersion modeling performed by Vistra's consultant AECOM using AERMOD version 19191 showed that AERMOD is conservative, and overpredicts strongly compared to SO_2 observations. AECOM has identified a detail in AERMOD's formulation related to its treatment of penetrated plumes as contributing to overpredictions in certain conditions, and suggested the use of an alternative formulation of AERMOD to better characterize dispersion when penetrated plumes are present.

Weil et al., (1997) first suggested the alternate formulation, the Highly-buoyant Plume Model (HIPMOD), for the treatment of penetrated plumes and more fully described it in Weil (2020) and Paine et al. (2020). The term "HIPMOD" as used by Weil et al., (1997) and Weil (2020) refers to a model formulation that adds important features that are not present in AERMOD. However, the computer code supplied by AECOM does not include all features described by Weil. The alternative model provided by AECOM refers to a variant of AERMOD that only has a different treatment of the penetrated plume component and is referred to as AERMOD-HBP.

The Texas Commission on Environmental Quality (TCEQ) contracted with Ramboll US Consulting, Inc. (Ramboll) to evaluate the model performance of AERMOD and AERMOD-HBP. The goal of the evaluation is to determine if an alternate model approval (AMA) demonstration can be made for the use of AERMOD-HBP under section 3.2 of Appendix W[2], *Guideline on Air Quality Models*, for use in the attainment demonstration state implementation plan (SIP) revision for the Rusk-Panola NAA.

This document describes the proposed model set up and evaluation procedures that will be applied to determine if AERMOD-HBP could be used for the attainment demonstration modeling required for the Rusk-Panola NAA SIP revision. The evaluation follows established statistical procedures described in *Protocol for Determining the Best Performing Model* (EPA, 1992).

Model evaluation will be performed based on SO_2 concentrations observed at two monitoring stations, Tatum CR 2181d Martin Creek Lake (referred to as Martin Creek) and Longview. The location of each monitor relative to the Martin Lake Generating facility is shown in **Figure 1-1**, and given in **Table 1-1**.

[1] https://www3.epa.gov/airquality/greenbook/tnp.html#SO2.2010.Rusk_Panola_Cos

[2] https://www.epa.gov/sites/production/files/2020-09/documents/appw_17.pdf

Table 1-1. Coordinates of Martin Lake Generating Facility, and Longview and Martin Creek SO_2 Monitors

Location	AQS Code	UTM Easting (m, Zone 15)	UTM Northing (m, Zone 15)	Bearing to Martin Lake Generating Facility (deg)	Distance to Martin Lake Generating Facility (km)
Martin Lake Generating Facility	-	352004	3570225	-	-
Martin Creek Monitor	484011082	352066	3572325	179°	2
Longview Monitor	481830001	338968	3583699	135°	19

Figure 1-1. Location of Martin Lake Generating Facility, and Longview and Martin Creek SO_2 Monitors

2. Dispersion Model Setup

This section describes the model setup that will be used to run AERMOD-HBP and AERMOD.

2.1 Source Parameters and Emissions

For the performance comparison, the TCEQ proposes to run both AERMOD and AERMOD-HBP with sources at the Martin Lake Generating Facility. Variable hourly actual emission rates, stack exhaust temperatures, and stack exit gas velocities were provided by Vistra on 25 January, 2021. Emission rates and stack parameters were based on 40 CFR Part 75 monitoring.

The Martin Lake Generating Facility contains three primary stacks that account for the bulk of SO_2 emissions. These sources were included in the models as point sources, with the locations provided in **Table 2-1**. Also provided are the elevation, height, and diameter of each stack. The location of each source is shown in **Figure 2-3**.

Table 2-1. Martin Lake Generating Facility Stack Locations and Source Parameters

Source ID	UTM Easting (m, Zone 15)	UTM Northing (m, Zone 15)	Elevation (m)	Stack Height (m)	Stack Diameter (m)
S1	351999	3570400	95.0	137.8	7.0
S2	352041	3570309	95.0	137.8	7.0
S3	352084	3570217	95.0	137.8	7.0

2.2 Meteorology

Meteorological input files created by TCEQ will be used for the evaluation. The meteorological data set was created by the TCEQ spanning the period of 2016 to 2020. Surface data was obtained from the National Weather Service (NWS) station at the East Texas Regional Airport (KGGG), located 19 km northwest of the Martin Lake Generating Facility, and collocated with the Longview monitor. Despite the 19 km distance, KGGG should be representative of conditions at the Martin Lake Generating Facility, due to the relatively flat surrounding terrain. To complete the five-year data set, regional data for 2016-2020 were downloaded for the NWS upper air station located at the Shreveport, Louisiana Regional Airport.

AERSURFACE (Version 20060) was used to develop surface characteristics for KGGG. NLCD 2016 TIFs of landuse, percent impervious, and tree canopy coverage for eastern Texas were used according to the updated guidance in the latest AERSURFACE User's Guide[3].

[3] https://gaftp.epa.gov/Air/aqmg/SCRAM/models/related/aersurface/aersurface_ug_v20060.pdf

AERMET (Version 19191) was used with regulatory default options to process surface data, landuse outputs from AERSURFACE, and the NWS upper air data. No onsite meteorological data was available for inclusion in AERMET. In the absence of on-site differential temperature measurements, the default Holtslag method was used for the stable boundary layer. The Adjust U* option was included to adjust friction velocities during low wind speed hours.

A wind rose showing the distribution of wind speeds and directions for the resulting 5-year data set is shown in **Figure 2-1**. The mean wind speed during the 5-year period was calculated to be 3.5 m/s. Winds are predominantly southerly, with few hours from the west. There are sufficient hours in the dataset with winds blowing towards the Martin Creek and Longview monitors to achieve statistically significant results.

The same AERMET-produced SFC and PFL files will be used to run both AERMOD and AERMOD-HBP. The models will be run separately for each monitor for the duration of available SO_2 concentration data; 2016 – 2020 at Longview, and 2018 – 2020 at Martin Creek.

Figure 2-1. Wind Rose and Meteorological Values for KGGG 2016 - 2020

2.3 Terrain Data and Receptor Grid

The evaluation of AERMOD-HBP and AERMOD will be done by placing a receptor at the location of the Martin Creek and Longview monitors. In addition, to account for known uncertainties in replicating spatiotemporal patterns in dispersion models, and to allow for more in-depth analyses, a "microgrid" of receptors was created. This grid was selected to span a 2° arc downwind from the Martin Lake Generating Facility to each monitor. **Figure 2-2** shows the microgrids at the Longview and Martin Creek monitors.

The 2° arc was selected to account for errors in wind direction measurements. As an example, the Gill WindSonic Anemometer User's Manual[4] lists an accuracy in wind direction readings of ±2°. At a downwind distance of 19 km (the distance of the Longview monitor from the Martin Lake generating facility), a 2° difference in wind direction translates to a 650 m difference in location of the maximum.

The spacing of the receptors is as follows:

- Longview
  - 30 degree spacing for radius of 20 m;
  - 24 degree spacing for radius of 60 m; and
  - 15 degree spacing for radii of 150 m, 250 m, and 500 m.
- Martin Creek
  - 30 degree spacing for radius of 20 m; and
  - 15 degree spacing for radius of 60 m.

Figure 2-2. "Microgrid" centered on the Longview (left) and Martin Creek (right) Monitors

[4] http://gillinstruments.com/data/manuals/windsonic-manual.pdf?iss=22.20151201

Receptor heights were processed using the AERMAP terrain processor (Version 18081) with elevation data from the National Elevation Dataset (NED), developed by the United States Geological Survey (USGS). The same receptor grid will be used to run both AERMOD and AERMOD-HBP.

2.4 Onsite Structures and Building Downwash Effects

Potential downwash effects on emissions plumes will be accounted for in the model by using building dimensions and locations (locations of building corners, base elevation, and building heights). Dimensions and orientation of onsite structures, as shown in **Figure 2-3**, will be input to the Building Profile Input Program for the Plume Rise Model Enhancements (BPIP-PRIME) v04274 program to calculate direction-specific dimensions and Good Engineering Practice (GEP) stack height information for input to AERMOD. A listing of the onsite structures to be included in the analysis, along with their heights above grade, base elevation, and the number of tiers included is provided in **Table 2-2**.

Figure 2-3. Martin Lake Generating Facility Source and Building Layout

Table 2-2. Martin Lake Generating Facility Building Parameters

Building ID	Elevation (m)	Height (m)	Number of Tiers
UNIT1	95.11	78.64[5]	8
UNIT2	95.11	78.64[5]	8
UNIT3	94.63	78.64[5]	8
TT1	95.04	60.96	1
CRSHTWR3	95.09	31.70	1
SURGSIL1	93.64	44.20	1
SURGSIL	91.29	44.20	1
ASHBIN1	94.46	24.38	1
ASHSILO1	94.45	42.67	1
ASHSILO2	94.45	42.67	1
SLDG1	94.71	18.29	1
ASHBTM3	96.16	24.38	1
ASHSILO3	96.47	42.67	1
ASHSILO4	96.47	42.67	1
SLDG3	96.90	18.29	1
LIMEBLG1	95.47	15.24	1
LIMEBDG2	97.36	6.10	1
LIMETNKS	96.10	6.10	1
FOTANK1	96.70	6.10	1
FOTANK2	96.21	12.19	1
LGHTWARE	94.86	6.10	1
HEVYWARE	94.61	6.10	1
SERVBLDG	95.34	6.10	1
OFFIC	96.60	6.10	1
CONSWRH1	96.16	6.10	1
CONST2	96.50	6.10	1
COND1	95.74	12.19	1
COND2	95.84	12.19	1
HOPPER1	91.47	6.10	1
HOPPER2	91.05	6.10	1
TT31	95.07	60.96	1

[5] Height of highest tier

2.5 Modeling Procedures

AERMOD and AERMOD-HBP will be run to produce hourly post files using the input data described above. These files produce an hourly time series of concentrations at each modeled receptor. All statistical calculations and inputs to further analyses will be performed using these hourly post files – no statistical calculations will be performed by the models.

3. Graphical Evaluation

While AERMOD and AERMOD-HBP share much of the same formulation, there are key situations in which they produce different concentrations. Dispersion in AERMOD-HBP is treated differently than AERMOD only when using the convective boundary layer. Therefore, concentrations only differ for those hours where the mixed layer height is between the bottom of the plume and the center of the plume. Both models are expected to produce identical results during stable (night-time) conditions; for hours when the entire plume is above the mixed layer (i.e., when the mixed layer height is shallow, early in the morning); and for those hours where the mixed layer height exceeds the plume height (i.e., when mixed layer is high, late in the day).

To ensure differences between the two models are as expected, daily trends in concentrations will be compared using plots of concentration grouped by hour of the day at Longview and Martin Creek monitors. Plots will be created for 90^{th}, 95^{th}, 99^{th}, and 100^{th} percentile concentrations.

Plots will compare observed and modeled (AERMOD and AERMOD-HBP) concentrations over the date of the n^{th} percentile observed values, as well as modeled concentrations during nth-percentile days. This means that daily concentration trends will be compared based on the statistic (e.g. 95^{th} percentile daily max value) in addition to presenting comparisons paired in time. Since AERMOD and AERMOD-HBP are statistical models, they do not excel at pairing concentrations in space and time, but do a good job of replicating the statistical distribution of observed concentrations datasets. Statistics are what should be compared between observations and predictions.

To further understand model performance across the distribution of observed and modeled values unpaired in time, quantile-quantile (QQ) plots that compare ranked hourly concentrations, with observations along the X axis, and model predictions along the Y axis will be created for the Longview and Martin Creek monitors by year.

4. Cox-Tikvart Analysis

As described in 3.2.2(d) of Appendix W, for alternate model approvals established statistical performance evaluation procedures should be used. The Cox-Tikvart method (EPA, 1992) has been used extensively for evaluating models. For the AERMOD-HBP evaluation, the Cox-Tikvart method was used to compare the model performance of AERMOD and AERMOD-HBP at the Martin Creek and Longview monitors.

4.1 Screening Test

As an initial screening step, the fractional bias of the average and standard deviation is used as a metric. For each station (Longview and Martin Creek) the SO_2 concentrations will be pooled by year and sorted by averaging period. From this data, the 25 highest observed concentrations unpaired in space or time, are used to calculate a mean and standard deviation. The same procedure is applied to the predicted concentrations obtained from the air dispersion models AERMOD and AERMOD-HBP, using the highest value over the receptor sets for each hour. Using these top 25 values, the fractional bias of the average and of the standard deviation are determined for each model for 1-hour, 3-hour and 24-hour averages. Fractional bias is calculated using Equation 1.

$$FB = 2 \cdot \frac{(Mean_{OBS} - Mean_{PRD})}{(Mean_{OBS} + Mean_{PRD})} \qquad (1)$$

It is important to note that the above equation will result in a *negative* bias when the model *overpredicts*, and a *positive* bias when the model *underpredicts*. A positively biased standard deviation indicates that there is less variance in the top 25 predicted values compared to observations.

Fractional biases will be calculated for 1-hour, 3-hour and 24-hour averaged concentrations. If fractional biases for most periods, years, and sites are within a factor of two (0.5 – 2), the model demonstrates adequate performance to proceed to more in-depth analyses.

4.2 Statistical Test

If AERMOD-HBP and AERMOD pass the screening test they will be subjected to a more comprehensive statistical comparison. The performance of AERMOD will be compared with the performance of AERMOD-HBP using a composite statistical measure that combines the performance of the scientific component (1-hour averages) and the operational component (3-hour and 24-hour averages).

The scientific component assesses the 1-hr averages during 6 specific meteorological conditions. The meteorological conditions are unique combinations of unstable (class A, B, C), neutral (class D), or stable (class E, F) conditions and wind speeds above or below 3 m/s. The 50th percentile of observed wind speeds is just over 3 m/s, so this cut-off value sorts the data approximately in half.

The Golder (1972) nomogram method will be used to convert AERMET's Monin-Obukhov length and roughness length to stability class, using Fortran code taken from the Mesoscale Model Interface Program (MMIF[6]).

The robust highest concentration (RHC) is a comparison of modeled and observed concentrations at the upper end of a frequency distribution and is calculated using Equation 2 where n=26, c_n is the nth highest concentration and $\bar{c}$ is the average of the (n-1) highest concentrations.

$$RHC = c_n + (\bar{c} - c_n) ln\left(\frac{3n-1}{2}\right) \qquad (2)$$

[6] See https://www.epa.gov/scram/air-quality-dispersion-modeling-related-model-support-programs#mmif

For each meteorological condition, the RHC is calculated for both the observed and modeled dataset and the fractional bias (FB) and absolute fractional bias (AFB) between the modeled and measured RHC are calculated using Equation 3 and Equation 4, respectively.

$$FB = 2 \cdot \frac{(RHC_{measured} - RHC_{modeled})}{(RHC_{measured} + RHC_{modeled})} \qquad (3)$$

$$AFB = \left| 2 \cdot \frac{(RHC_{measured} - RHC_{modeled})}{(RHC_{measured} + RHC_{modeled})} \right| \qquad (4)$$

The operational component evaluates the peak 3-hour and 24-hour averages independent of meteorology or spatial location. The absolute fractional bias between measured and modeled RHC is calculated in a similar manner, except that the data is grouped into 3-hour and 24-hour averages, respectively.

A composite performance metric (CPM) combines the 1-hr, 3-hr, and 24-hr absolute fractional biases in RHC for both the scientific and operational components, as shown in Equation 5.

$$CPM = \frac{(\ average(AFB(i,j) + AFB(3) + AFB(24))}{3} \qquad (5)$$

where AFB(i,j) is the absolute fractional bias for each meteorological condition and each station, AFB(3) is the absolute fractional bias for 3-hour averages, and AFB(24) is the absolute fractional bias for 24-hour averages.

The CPM is lowest when there is a good agreement between measured and modeled RHC values. Comparing the magnitudes of the CPM values from different models using the same observational data quantizes performance of each dispersion model.

To improve the robustness of data used for model comparison, a statistical technique known as bootstrapping will be used to generate a probability distribution of outcomes. The bootstrap method resamples the available data into three-day blocks. These blocks are grouped by season (regardless of year), then sampled with replacement until a full season of data is created. After 1,000 iterations of this process, the standard deviation of generated runs is used as the standard error for model comparison. The Python script used to run the bootstrap analysis is available upon request.

To highlight differences between models, and to determine which model performs better, the Model Comparison Measure (MCM) is used. This is simply the difference in CPM between two models, as described by Equation 6.

$$MCM = CPM(a) - CPM(b) \qquad (6)$$

A positive MCM indicates better performance from model b than model a, and vice-versa.

4.3 Cox-Tikvart Scenario Description

To provide deeper insights into differences between the models, the Cox-Tikvart method will be performed for three scenarios:

1. **Standard Methodology** - One modeled receptor placed at the location of the monitor, with concentrations from both sites pooled.

2. **Single Receptor -** One modeled receptor placed at the location of the monitor, with concentrations from each site treated separately.

3. **2° Microgrid –** Max hourly concentrations from a microgrid of modeled receptors centered on the monitor, with concentrations from each site treated separately.

Option 1 is consistent with the standard Cox-Tikvart methodology (EPA, 1992). However, options 2 and 3 will provide more insights into the differences between the dispersion models and as an assessment of their use for regulatory purposes.

Since the RHC is calculated using the top 25 values, and concentrations at a receptor 2 km downwind will generally be much higher than those at 19 km, if sites are pooled, RHC values will be dominated by near-field concentrations. Evaluating each site independently will highlight model performance at a range of distances.

Evaluating model performance at a single receptor is not representative of regulatory use cases for dispersion models – they are almost always run with a grid of receptors covering the entire modeling domain. Using the maximum across a grid of receptors will allow for comparison during hours when errors in wind direction readings might cause a plume to "miss" a receptor. The use of a 2° microgrid – derived from the error range of modern wind sensors is proposed.

5. Comparison to EPA Model Evaluations

To contextualize the Cox-Tikvart results of the comparison of AERMOD-HBP and AERMOD an examination of EPA's Model Evaluation Databases[7] and their discussion in EPA's 2003 paper "*AERMOD: Latest Features and Evaluation Results*"[8] is proposed. EPA's 2003 paper primarily evaluates model performance by examining the ratio of the model-predicted RHC to observed RHC. The various tracer studies were used for model formulation and/or validation. A summary of these studies and their results is provided in **Table 5-1**. This table also summarizes the study duration, whether the model was used for development or independent validation, the distance to the nearest and farthest monitors/receptors, whether the model over or under predicted, and the ratio of the predicted RHC to observed RHC.

[7] See https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

[8] See https://gaftp.epa.gov/Air/aqmg/SCRAM/models/preferred/aermod/aermod_mep.pdf (454-R-03-003)

For the purposes of this study, the independent datasets are the most relevant, as this analysis is independent of any sort of model formulation. While the development studies showed a mix of over and underprediction, all but one of the independent studies resulted in an RHC ratio above 1 (overprediction), (not including the Lee Power Plant Wind Tunnel study under neutral conditions - maximum concentrations generally occur under stable conditions). However, RHC values were calculated using the top 25 values for the entire dataset, irrespective of space and time (like the proposed “Standard Methodology” for this study). These 25 values almost certainly occur at one of the closest receptors. Since many of these studies’ closest receptors are around the same range as the distance to the Martin Creek monitor, these results are directly comparable.

The Longview monitor, however, is 19 km from the Martin Lake Generating Facility. The farthest receptor in the Kincaid study was 20 km from the source. However, this study was used for model development. The independent study with receptors farthest from the source, at 15 km, is the Clifty Creek study[9], which ran for a full year. To observe performance at various distances from the source 1-hour RHC values at each receptor was calculated independently using AERMOD Post files and records of observations. These values are provided in **Table 5-2**.

[9] AERMOD inputs/outputs and observed concentrations from the Clifty Creek study are available for download at https://gaftp.epa.gov/Air/aqmg/SCRAM/models/preferred/aermod/eval_databases/clifty.zip

Table 5-1: Summary of EPA AERMOD Model Evaluation Studies

Name	Duration	Model Development/ Independent	Min Source to Receptor Distance (m)	Max Source to Receptor Distance (m)	1hr or 3hr MOD/OBS RHC Ratio	Under/Over Prediction
Kincaid	2 x 6 weeks	Development	450	20000	0.77	Under
Kincaid	6 months	Development	2000	20000	0.98	Under
Lovett	1 year	Development	2000	3650	1.03	Over
Alaska North Slope Tracer Study	44 hours	Development	17	3399	1.06	Over
Millstone	36 hours	Development	350	1500	0.44	Under
Duane Arnold Energy Center	12 + 16 + 11 hours	Development	300	1000	0.69	Under
Prairie Grass	44 ten-min samples	Development	50	800	0.89	Under
Bowline	1 year	Development/ Independent	250	800	1.14	Over
Clifty Creek	1 year	Independent	3000	15000	1.05	Over
Baldwin	1 year	Independent	1300	10000	1.24	Over
Tracy	128 hours	Independent	3000	10000	1.04	Over
Martins Creek	1 year	Independent	3000	8000	1.12	Over
Indianapolis	700 hours	Independent	300	6000	1.11	Over
Westvaco	1 year	Independent	780	1500	1.06	Over
Lee Power Plant wind tunnel study	78 hours	Independent	450	900	0.51 (neutral) 2.50 (stable)	Under
Experimental Organic Cooler Reactor	22 hours	Independent	800	800	1.72	Over
American Gas Association	63 hours	Independent	200	200	0.92	Under
Westar NO_2	6 weeks	Not used	55	125	--	--

Table 5-2. Clifty Creek Model Evaluation RHC Ratios by Receptor

UTM Easting (m)	UTM Northing (m)	1 Hour Predicted RHC	1 Hour Observed RHC	1 Hour RHC Ratio (Prd/Obs)	Distance from Source (km)
646890	4300090	767	1149	0.67	15.0
641970	4299200	909	1422	0.64	11.6
645150	4287350	987	542	1.82	8.0
643380	4292740	1061	1012	1.05	7.4
638490	4292930	1535	948	1.62	4.5
637570	4285520	1152	892	1.29	3.1

The RHC ratio for the Longview and Martin Creek monitors will be calculated to allow comparison to the Clifty Creek study. If RHC ratios produced by AERMOD-HBP over the Martin Lake modeling domain indicate better performance than those shown in previous EPA studies, it can be said that in this specific use case, AERMOD-HBP meets model performance requirements for regulatory evaluations.

6. References

1. Environmental Protection Agency, 1992. Protocol for Determining the Best Performing Model (EPA-454/R-92-025). U.S. Environmental Protection Agency, Research Triangle Park, NC.
2. Golder, 1972. Relations among stability parameters in the surface layer. Boundary-Layer Meteorology, 3:56.
3. Gill Instruments Limited, 2015. WindSonic Ultrasonic Anemometer User's Guide. Available at http://gillinstruments.com/data/manuals/windsonic-manual.pdf?iss=22.20151201
4. Weil, J.C., L.A. Corio, and R.P. Brower, 1997: A PDF dispersion model for buoyant plumes in the convective boundary layer. *J. Appl. Meteor.*, 36, 982–1003.
5. Weil, J.C., 2020. New Dispersion Model for Highly-Buoyant Plumes in the Convective Boundary Layer. Preliminary Draft V4.
6. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume II – Description of Model Algorithms. USEPA/OAQPS, EPA-454/B-95-003b, September 1995. Available at https://gaftp.epa.gov/Air/aqmg/SCRAM/models/other/isc3/isc3v2.pdf
7. Paine, R., C. Szembek, and C. Warren, 2020. Overview of the Highly-buoyant Plume (HIPMOD) Model. October 15, 2020.

The Alternative Modeling Approach for Highly Buoyant Plumes in AERMOD

AECOM

May 1, 2024

Background

1-Hour SO_2 NAAQS

The United States Environmental Protection Agency (EPA) established a new 1-hour National Ambient Air Quality Standard (NAAQS) for sulfur dioxide (SO_2) of 75 parts per billion (ppb) on June 2, 2010. Relying on Sierra Club's dispersion modeling of SO_2 emissions from the Martin Lake Power Plant using AERMOD (EPA's preferred short-range dispersion model) with default settings, EPA designated portions of Rusk and Panola Counties as a nonattainment area (NAA) for the 2010 SO_2 primary NAAQS on December 13, 2016, effective as of January 12, 2017. In response to this designation, the Texas Commission on Environmental Quality (TCEQ) prepared a State Implementation Plan (SIP) revision to demonstrate future attainment of the NAAQS and submitted the SIP revision to EPA for its review.

In support of its SIP revision, on May 24, 2021, TCEQ submitted a request to EPA Region 6 pursuant to 40 CFR Part 51, Appendix W, Section 3.2.2(b)(2) for the use of an alternative model in the Rusk-Panola County SIP revision. The alternative model requested by TCEQ is a variation of AERMOD that includes an alternative formulation to more accurately treat plumes that break through the top of the convective boundary layer, referred to as AERMOD-HBP. TCEQ provided EPA with AERMOD-HBP formulation documents and a model performance evaluation of both AERMOD and AERMOD-HBP using the evaluation procedures recommended in 40 CFR Part 51, Appendix W, as part of their submittal package. TCEQ's request remains pending; however, it appears that EPA has begun processing this request under the Appendix W procedures. In a March 6, 2024 email from Mr. Erik Snyder, Lead Air Quality Modeler for EPA Region 6, to AECOM, Mr. Snyder requested additional information regarding the AERMOD-HBP model formulation and coding. This report is being submitted in response to that request by EPA.

Dispersion Model Evaluation

TCEQ's alternative model request is based on a comparative analysis of AERMOD using regulatory, default options modeling to actual monitoring data collected pursuant to EPA's Data Requirements Rule (DRR) for the Rusk and Panola Counties area. Consistent with the DRR, on June 26, 2016, TCEQ notified EPA that it was selecting to use monitoring data for purposes of designating areas in Texas under the 2010 1-hour SO_2 NAAQS.[1] As a result, TCEQ installed an ambient SO_2 monitor ("Tatum CR 2181d Martin Lake Creek"), hereafter referred to as the Martin Lake Creek monitor, in late 2017 about 2 kilometers (km) north of Martin Lake where dispersion modeling (using default options in AERMOD) indicated the peak impacts from the plant would be located. The information collected by the Martin Lake Creek monitor has since been used to characterize SO_2 concentrations in an area of expected peak concentrations near the plant in order to supplement and verify the results of the AERMOD modeling. Importantly, this monitor has also shown attainment of the NAAQS for the most recent 3-year period, with a preliminary design value below 70 ppb for 2021-2023, with 2023 itself showing a markedly lower design value of about 40 ppb following emission reductions at Martin Lake.

[1] Federal Register. Volume 84, No. 163. 40 CFR Part 81. pp. 43757-43760. Available at: https://www.govinfo.gov/content/pkg/FR-2019-08-22/pdf/2019-18048.pdf

After three complete years (2018-2020) of ambient SO_2 data collected at the Martin Lake Creek monitor, AECOM Technical Services, Inc. (AECOM) conducted a model performance evaluation of AERMOD using regulatory, default options, at the request of Martin Lake. The model performance evaluation demonstrated that the regulatory, default model overpredicts at the monitored location. The underlying cause of the overprediction is due to the model's inability to accurately and appropriately treat the dynamics of the portion of the exhaust plume that rises into the elevated stable layer, above the convective mixed layer. This plume type is referred to as the "penetrated plume", which is significantly buoyant enough to break through the upper cap of the mixed layer and into this stable layer. In certain cases, AERMOD models a penetrated plume as mixing into the convective layer well before the convective mixed layer has risen to intercept the plume. As a result, AECOM implemented an alternative approach to correct for the penetrated plume issue in AERMOD and provided this to TCEQ in May 2021. TCEQ used this information to perform their own independent evaluation of AERMOD-HBP as compared to AERMOD and develop its SIP revision. This information was then submitted to EPA Region 6 in TCEQ's request for approval of an alternative model under Appendix W.

The alternative model implemented by AECOM that was provided to TCEQ in May 2021 is the same one that is described in detail in the section below titled "HBP Formulation in AERMOD." Further, after TCEQ submitted its revision and Appendix W request to EPA in May 2021, the HBP formulation has been peer-reviewed and published in the Journal of the Air and Waste Association (Warren et al., 2022), and EPA released an updated version of AERMOD (version 23132) that includes the same HBP formulation as an ALPHA option (EPA 2023).

Request by EPA

In March 2024, Mr. Erik Synder of EPA Region 6 contacted AECOM to request additional supporting documentation on the formulation of HBP in AERMOD. Thus, this document serves to fulfill this request and provide background information on how HBP was developed and evaluated for modeling 1-hour SO_2 concentrations for Martin Lake.

Penetrated Plume Treatment in AERMOD

Behavior of the Penetrated Plume

The issue of the penetrated plume has been studied by researchers for decades. AERMOD has a three-plume treatment for stack emissions in convective conditions: direct, indirect, and penetrated components (**Figure 1, *Three-plume Treatment by AERMOD in Convective Conditions***). For any given hour, the plume mass can be divided into as many as all three of these plume cases. As shown in **Figure 1**, the direct and indirect plumes remain within the convective mixed layer, which features vigorous vertical mixing above the surface layer (the lowest ~10% of the mixed layer).The actual behavior of the penetrated plume is that it rises into the stable layer above the convective boundary layer and is subsequently mixed to the ground only when the convective mixing height rises to intercept it. A conceptual diagram of the nature of the penetrated plume from the Weil et al. (1997) paper[2] as shown in **Figure 2, *Depiction of Penetrated Plume Aloft***, indicates that the penetrated plume mixes to the ground over time, and not necessarily during the same hour that it is emitted into the stable layer aloft.

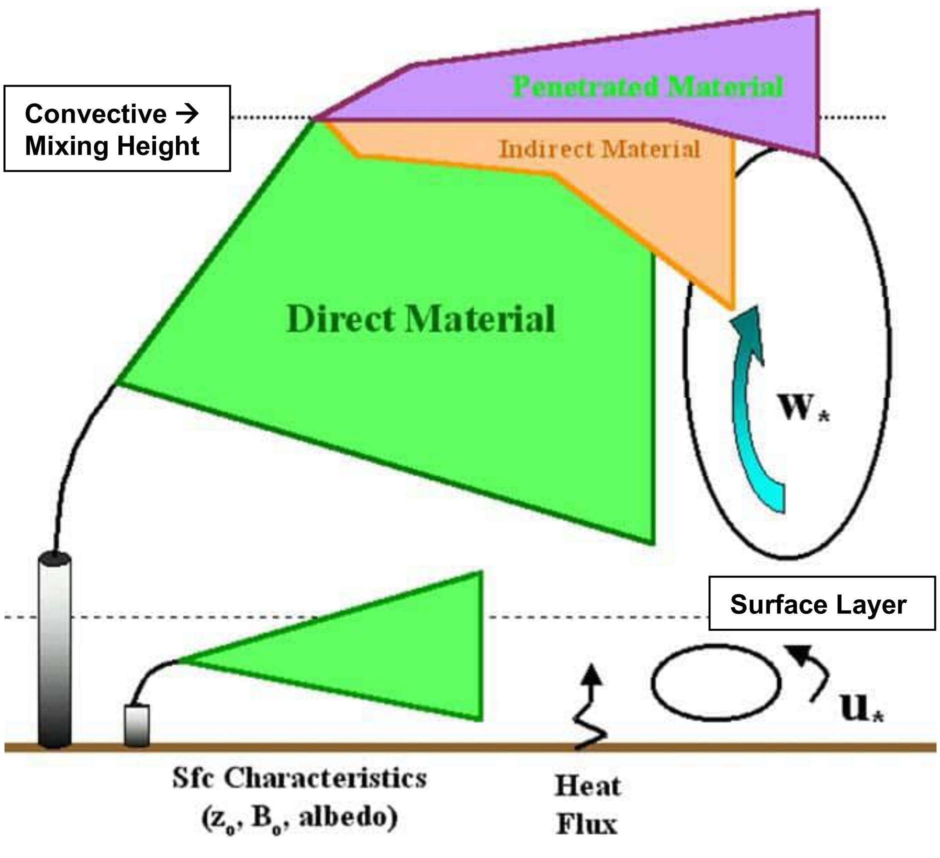
This phenomenon has been documented through field work, which includes research-grade experiments in the 1980s that detected plume concentrations aloft using laser imaging, detection, and ranging ("LIDAR") instrumentation. The methods used for the EPRI Kincaid and Bull Run field studies are described by Moore et al. (1988) and are provided as **Attachment 1**. Remote-sensing observations of the plume aloft were made by ground-based, mobile SO_2, differential adsorption LIDAR ("DIAL"), ground-based, mobile particle-

[2] Dr. Weil and Robert Paine (one of the AECOM authors of this document) were members of the AERMOD development team.

sensing LIDAR, and airplane-based particle LIDAR known as an airborne LIDAR plume and haze analyzer ("ALPHA-I"). The SO_2 DIAL instrument measured the absolute SO_2 concentrations of the plume aloft. For the LIDAR to observe the entire plume cross-section, it had to be operated within 2 km of the stack at Kincaid and within 1 km at Bull Run. The ground-based LIDARs scanned the plume through a plane normal to the plume centerline aloft and through a plane parallel to the ground-level concentration pattern.

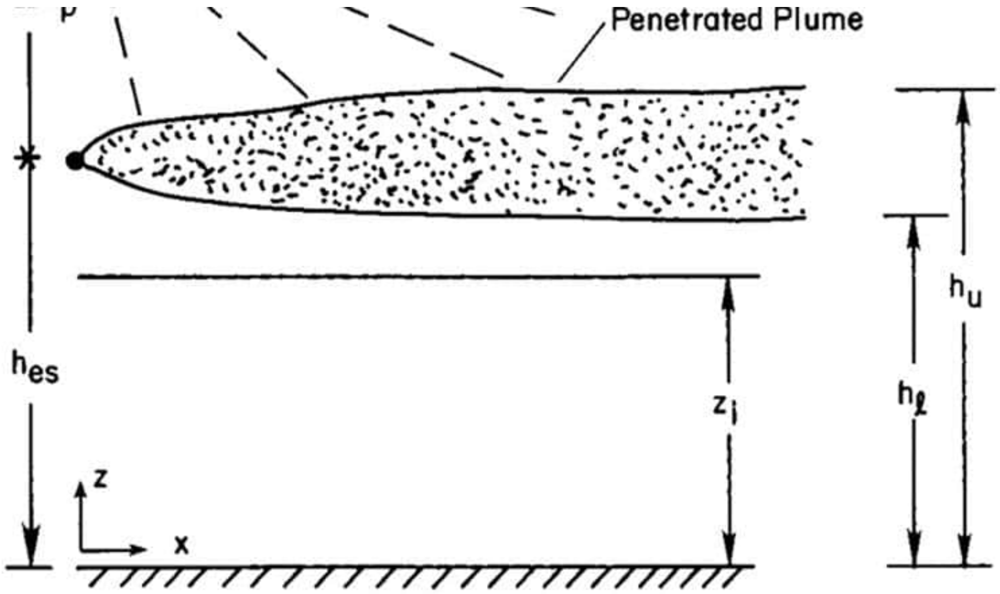
Inversion heights associated with the convective mixed layer height for the Kincaid and Bull Run field studies were determined throughout the daytime period from frequent tethersonde[3] soundings. Vertical plume cross sections were determined from the remote sensing measurements, and plume concentrations in parts per billion (ppb) were mapped for several hourly averaging periods.

Figure 1: Three-plume Treatment by AERMOD in Convective Conditions



[3] A tethersonde is a radiosonde attached to a fixed or tethered balloon.

Figure 2: Depiction of Penetrated Plume Aloft by Weil et al., 1997[4]



[4] From Weil et al, 1997, where h_{es} is the stabilized plume height, z_i is the mixing height, h_l and h_u are the lower and upper penetrated plume heights, respectively.

Figures 3 through **6**, ***LIDAR Images from Bull Run,*** show an example of the time evolution of the plume behavior during one morning at Bull Run up to the time that the convective mixing height (marked in red in each figure) intercepted the plume aloft. The figures, which cover four separate hours for that day, show the integrated plume concentration in the X-Z plane. Basically, the compact nature of the plume was preserved until the noon hour (the last in the series, **Figure 6**) when the convective mixing height finally rose through the layer occupied by the plume. This behavior shows that prior to this time, the penetrated plume remained above the mixing height and did not mix down to the ground until it was intercepted by the rising convective mixed layer. The maximum ground-level concentrations for this case were about four times higher during the hour 1200-1300 than the preceding hours that day. The plume centerline concentrations aloft were about a factor of four lower after mixing throughout the convective boundary layer.

Figure 3: Lidar Image from Bull Run, October 4, 1982, 8-9 AM

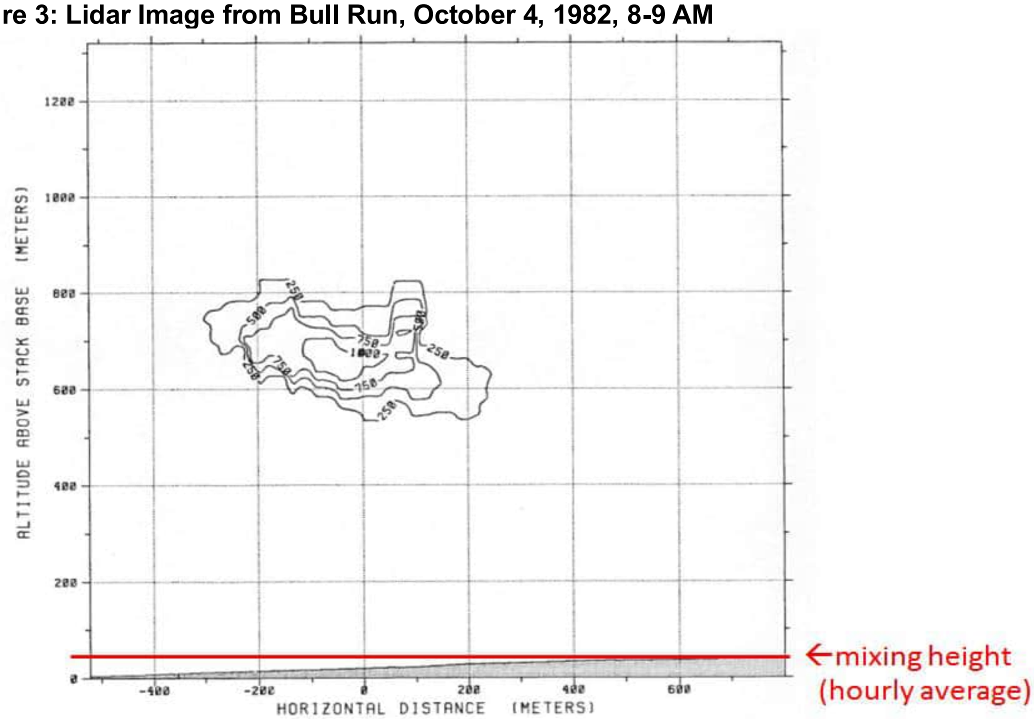


Figure 4: Lidar Images from Bull Run, October 4, 1982, 10-11 AM

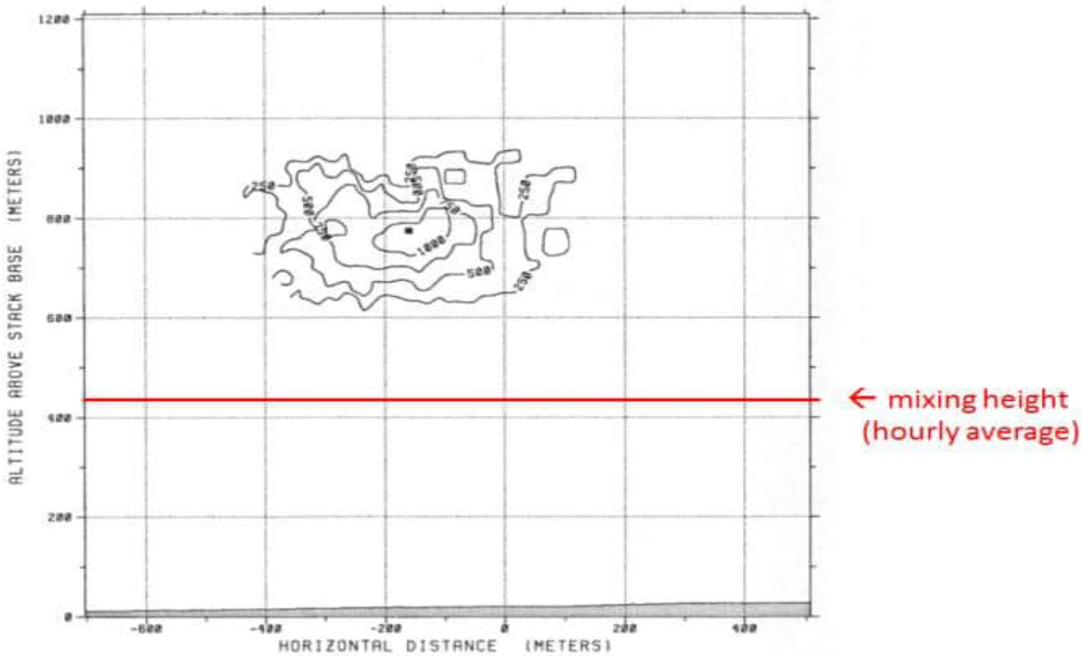


Figure 5: Lidar Image from Bull Run, October 4, 1982, 11 AM - noon

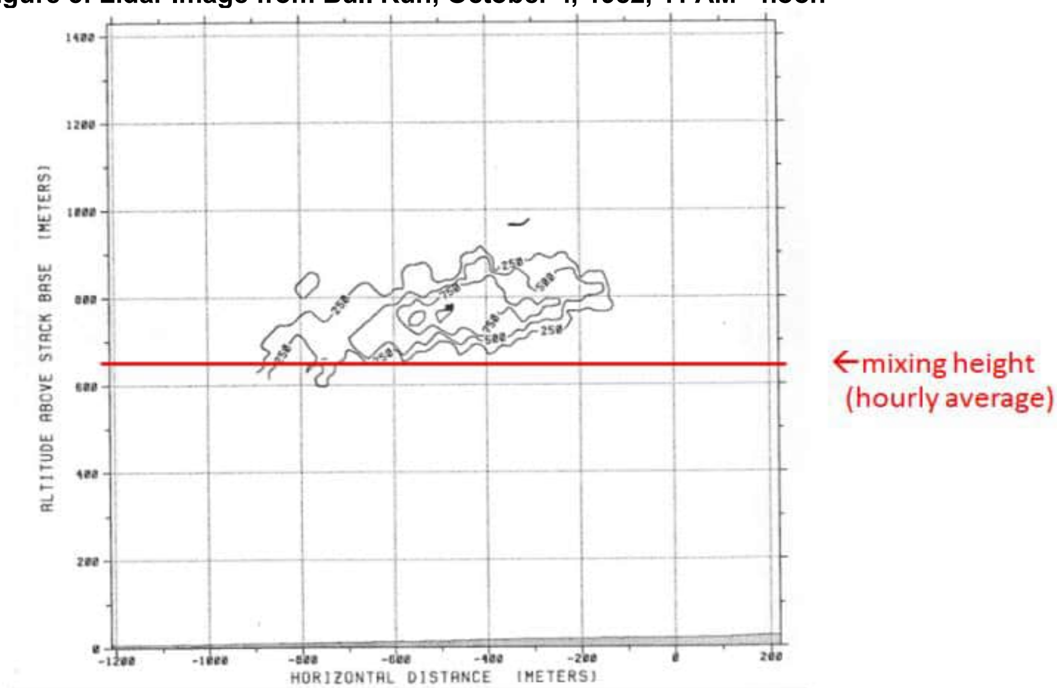
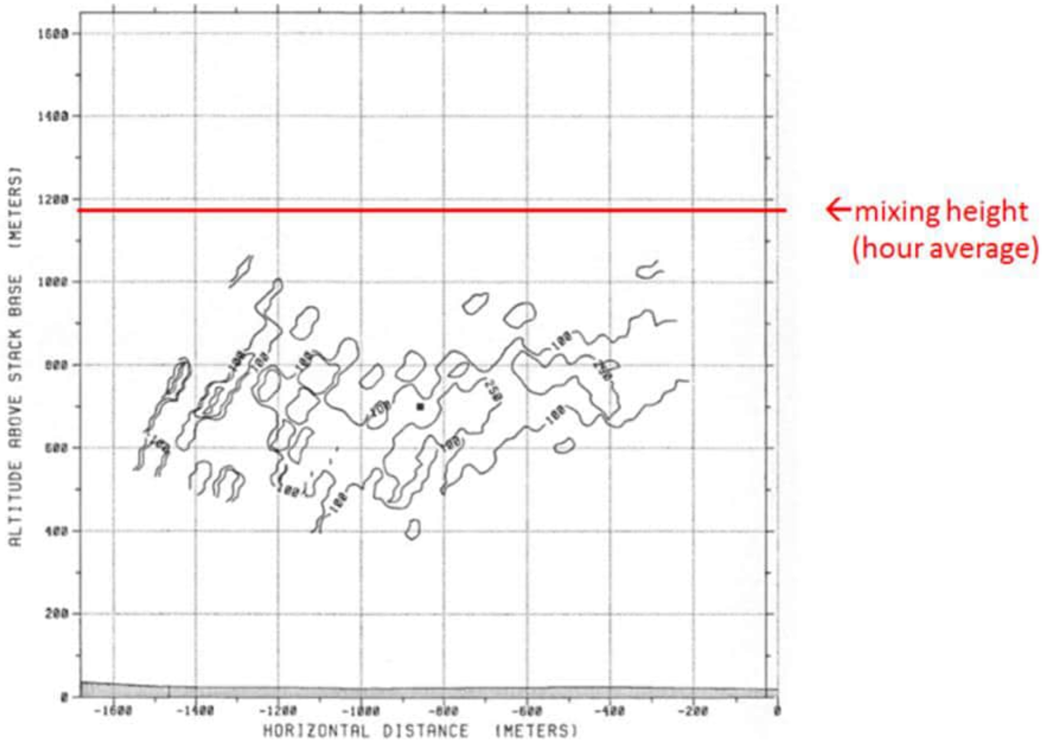


Figure 6: Lidar Image from Bull Run, October 4, 1982, noon – 1 PM



Based upon the findings noted above, the likelihood of elevated ground-level concentrations resulting from a penetrated plume is low until the convective mixed layer has risen to intercept the plume. The penetrated plume interception event, often referred to as "daytime fumigation," typically leads to elevated concentrations only during a single hour of the day. The multiple-hour evolution of this process, as shown in **Figure 3** through **Figure 6**, presents a challenge because AERMOD is a steady-state model and has no information, absent the proposed enhancements discussed below, of the next hour's conditions.

Current Implementation in AERMOD

The regulatory AERMOD version 23132 (released on October 12, 2023) with default options does not accurately model this phenomena and results in the mixing of the penetrated plume into the convective boundary layer during more hours than expected, resulting in a premature and repetitious mixing of the penetrated plume to the ground that only occurs once during the daytime hours.[5] Because this premature mixing assumption is repeated for multiple hours leading up to the actual interception of the penetrated plume by the rising convective boundary layer ("CBL"), AERMOD will overstate the frequency of the plume mixing events, resulting in overpredictions. This issue with AERMOD has been observed by investigators associated with field studies where the model is found to overpredict ground-level concentration events due to the penetrated plume issue and make those predictions too often and too early in the day, by as much as 2-4 hours, as compared to the timing of observed ground-level impacts.

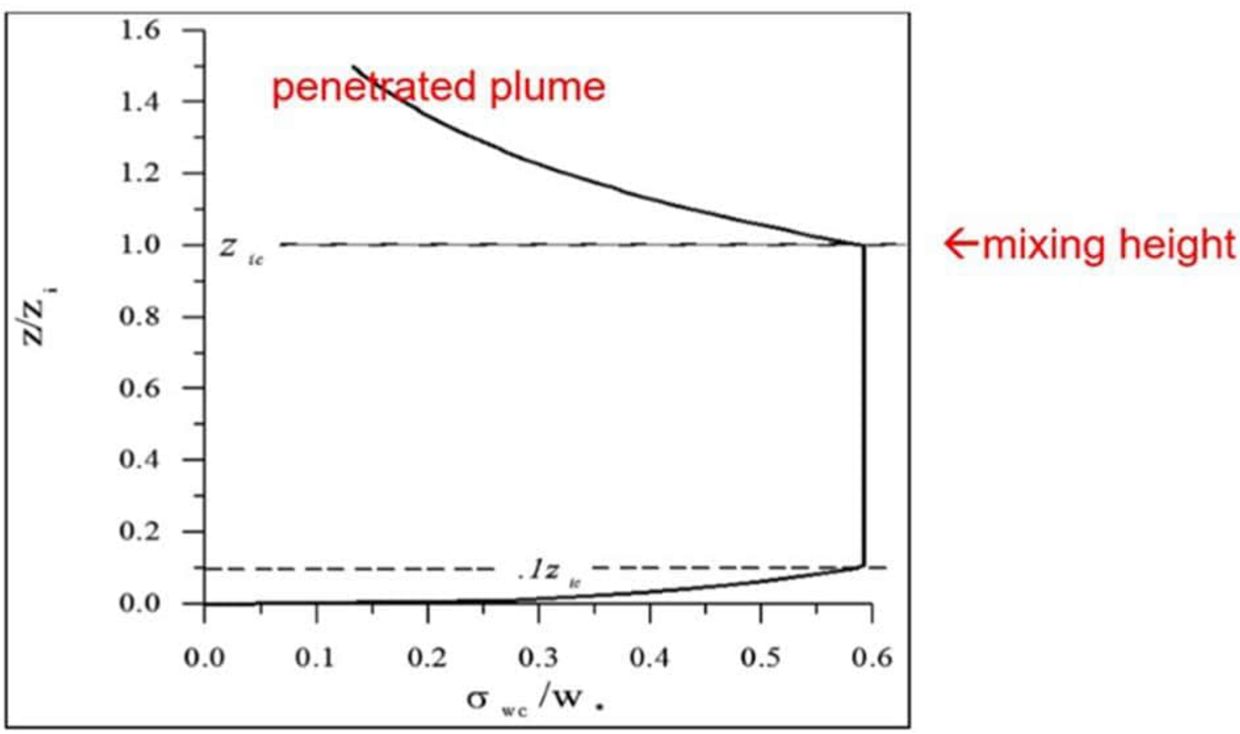
A key area of scrutiny in the AERMOD formulation is the parameterization of the penetrated plume's vertical spreading through its calculation of "effective" dispersion parameters. AERMOD's formulation computes vertically integrated values between the plume centerline and the higher level of the plume's bottom edge and receptor at the ground. However, this calculation can substantially overstate the vertical plume growth if the wrong vertical plume depth (a function of vertical plume dispersion, sigma-z) is assumed by the model.

[5] It is worth noting that this mistreatment of the penetrated plume in AERMOD has existed since it was promulgated by EPA as the preferred short-range dispersion model in November 2005.

The central issue for the penetrated plume handling in AERMOD is that the computation of sigma-z (used to determine the plume's bottom edge) is a function of the stability in the layer occupied by the plume. By definition, the penetrated plume is in a stable layer above the mixing height, but the AERMOD formulation assumes a neutral layer for computing the penetrated plume sigma-z, which substantially and incorrectly increases the sigma-z value. This formulation, according to the AERMOD model formulation document (EPA 2023), assumes that the penetrated plume mixes into the CBL and thus encounters a non-stable layer for the portion of the plume that reaches the ground. However, this assumption is only correct if the mixing height rises fast enough to capture at least a portion of the penetrated plume by the end of the current hour, according to Weil (Weil et al. 1997). Otherwise, this assumption is incorrect as evidenced by the direct observations of the actual penetrated plume behavior (such as at Bull Run) not mixing down from the stable layer aloft while the CBL remains below the plume.

AERMOD computes the "effective" values for turbulence parameters (vertical turbulence, sigma-w in particular) that involves averaging through a vertical depth between the plume centerline to the bottom of the plume, which is a distance of 2.15 sigma-z below the plume centerline. With the incorrect assumption of a large sigma-z for a penetrated plume, AERMOD averages sigma-w over a depth that, in reality, can involve large changes in sigma-w with height above the mixing height (see **Figure 7, *AERMOD's Treatment of Vertical Turbulence in Convective Conditions***). Hence, for hours when the actual mixing height has yet to intercept the plume, the averaged, computed value does not represent local turbulence conditions at the penetrated plume's centerline height. For many cases, where the vertical integration occurs over a significant depth within the convective boundary layer, the modeled plume spreading will be greatly exaggerated because the actual values of sigma-w in the convective boundary layer can be an order of magnitude higher than those in the stable layer aloft.

Figure 7: AERMOD's Treatment of Vertical Turbulence in Convective Conditions



Debugging of AERMOD to Understand the Penetrated Plume Issue

Due to AERMOD's three-plume treatment as shown in **Figure 1**, the findings noted above for the penetrated plume can be difficult to diagnose. The "Model Debug" output from AERMOD is one way to review plume behavior in AERMOD, but the file size for the output is so large that its use is impractical for routine modeling applications. This awkward debug file issue led AECOM, with funding from EPRI, to develop a more streamlined "DISTANCE DEBUG" output that lists the coherent plume statistics for only the peak impact receptor for each source and each hour, thus resulting in a manageable output size that is still useful. This tool has been documented in a conference presentation (Szembek et al. 2017, provided as **Attachment 2**) as well as TCEQ's submittal[6] to EPA in 2016, which explains (on page 162 of 269):

> *"the "DISTANCE DEBUG" output capability of AERMOD is documented and freely available from EPRI at https://sourceforge.net/projects/epri-dispersion/", and that the "review of Sierra Club modeling results for Martin Lake [relied upon by EPA for their nonattainment designation] that were re-run with a 'DISTANCE DEBUG' enhanced AERMOD debugging output confirms that the Martin Lake peak AERMOD-predicted concentrations are caused by the simulated penetrated plume."*

Two examples of how various the debug output data obtained from AERMOD show the current problem with the penetrated plume are discussed in the following subsection.

Examples of Martin Lake Penetrated Plume Overprediction Issues

AERMOD modeling conducted with three years of data (2018-2020) shows that the model, using default options, overpredicts the 3-year design concentration (3-year average of the 99th percentile peak daily 1-hour maximum concentration) at the monitoring site by about 30%. This overprediction tendency would result in an initial 30% penalty for Martin Lake to show NAAQS compliance with a reduced emission rate. The cause of the overprediction has been determined to be the penetrated plume and the top ten AERMOD predictions are all dominated by the penetrated plume issue, as shown in the DISTANCE-DEBUG output (**Table 1, *Excerpts of DISTANCE-DEBUG Output for Top 10 Daily Maxima AERMOD Default Impacts at Martin Lake Creek Monitor***).

The combination of AERMOD's MODEL and METEOR debug files, in addition to the DISTANCE-DEBUG output files, were used to diagnose the penetrated plume issue with the default, regulatory-approved AERMOD model. Two specific Martin Lake events are discussed below, the first occurring on June 3, 2019, at hour 11 and the second on June 29, 2019, at hour 11.

[6] Available at https://www.tceq.texas.gov/assets/public/implementation/air/sip/so2/2015RevisedRecommendation/041916_SO2_Designation_120-Day_Response.pdf.

Table 1: Excerpts of DISTANCE-DEBUG Output for Top 10 Daily Maxima AERMOD Default Impacts at Martin Lake Creek Monitor

Daily Maxima RANK	YYMMDDHH	TOTAL Conc. (µg/m³)	u* (m/s)	w* (m/s)	OBULEN (m)	Z_{mech} (m)	Z_{conv} (m)	SFC Z_0 (m)	Source ID	Actual Emissions (g/s)	Ts (K)	Vs (m/s)	Final Plume Height (FPH) (m)	Distance to FPH (m)	WDIR @ FPH (deg.)	Effective Wind Speed (m/s)	Plume Type	Meander Fraction	Partial Penetration Fraction	Effective Sigma V (m/s)	Effective Sigma W (m/s)	Hourly Conc. (µg/m³)
1	18090609	666.1	0.14	0.74	-5.2	130	285	0.032	S1	*875.4*	*360.2*	*33.7*	445.5	924.9	77	1.9	PEN	0.177	1.000	0.51	0.36	210.3
									S2	*824.3*	*347.7*	*29.8*	419.3	924.9	77	1.8	PEN	0.179	0.969	0.51	0.38	218.9
									S3	*972.8*	*363.1*	*32.4*	445.6	924.9	77	1.9	PEN	0.177	1.000	0.51	0.36	221.8
2	20032213	619.2	0.14	0.67	-7.3	125	322	0.025	S1	*0.3*	*306.4*	*2.3*	238.8	307.6	80	2.0	IND	0.147	0.075	0.48	0.42	0.1
									S2	*1097.6*	*361.7*	*31.8*	418.9	1227.1	80	2.0	PEN	0.141	0.769	0.48	0.38	321.8
									S3	*920.6*	*347.7*	*29.1*	405.6	1227.1	80	2.0	PEN	0.142	0.714	0.48	0.38	282.2
3	18022211	604.5	0.20	0.49	-42.1	213	259	0.02	S1	*728.1*	*345.5*	*33.1*	324.5	1656.1	82	3.5	PEN	0.052	0.779	0.48	0.31	184.2
									S2	*866.0*	*362.0*	*33.4*	332.1	1791.4	82	3.5	PEN	0.052	0.820	0.48	0.31	221.8
									S3	*701.7*	*358.3*	*34.9*	332.4	1795.8	82	3.5	PEN	0.052	0.821	0.48	0.31	183.5
4	18101910	585.8	0.13	0.43	-11.9	117	186	0.027	S1	*507.0*	*361.2*	*28.8*	348.7	965.2	77	1.9	PEN	0.094	1.000	0.35	0.15	167.0
									S2	*585.2*	*348.1*	*27.2*	334.1	965.2	77	1.9	PEN	0.095	1.000	0.35	0.17	227.6
									S3	*469.4*	*346.8*	*26.9*	332.1	965.2	77	1.9	PEN	0.095	1.000	0.35	0.17	176.2
5	18123011	572.2	0.13	0.45	-19.3	114	317	0.02	S1	*946.6*	*346.2*	*32.4*	378.2	1692.4	74	2.1	PEN	0.082	0.609	0.37	0.28	233.2
									S2	*555.1*	*347.8*	*20.5*	362.6	1420.6	74	2.1	PEN	0.083	0.506	0.37	0.28	126.6
									S3	*998.6*	*343.3*	*31.9*	376.1	1657.1	74	2.1	PEN	0.082	0.596	0.37	0.28	197.5
6	18061907	479.6	0.22	0.64	-29.6	244	303	0.032	S1	*715.5*	*362.0*	*34.8*	397.9	1703.9	82	3.5	PEN	0.066	0.802	0.56	0.38	132.3
									S2	*935.4*	*366.3*	*31.8*	395.8	1676.4	82	3.5	PEN	0.067	0.794	0.56	0.39	182.7
									S3	*746.3*	*359.4*	*33.7*	394.6	1660.9	82	3.5	PEN	0.067	0.789	0.56	0.39	149.5
7	18102210	468.3	0.16	0.77	-5.9	154	266	0.027	S1	*599.3*	*351.6*	*27.2*	363.2	957.5	85	2.2	PEN	0.150	0.904	0.55	0.42	171.9
									S2	*449.5*	*347.5*	*25.5*	357.4	957.5	85	2.2	PEN	0.151	0.882	0.55	0.42	138.0
									S3	*459.0*	*345.4*	*27.2*	359.1	957.5	85	2.2	PEN	0.151	0.888	0.548	0.42	143.4
8	20100910	464.8	0.23	0.74	-25.7	258	365	0.027	S1	*913.8*	*349.0*	*28.3*	435.0	1470.9	82	3.7	PEN	0.071	0.572	0.61	0.46	146.8
									S2	*1068.4*	*368.0*	*33.7*	456.6	1737.6	82	3.7	PEN	0.070	0.669	0.61	0.45	154.1
									S3	*930.1*	*357.5*	*29.5*	442.8	1568.0	82	3.7	PEN	0.071	0.610	0.61	0.46	149.0
9	18012711	459.7	0.10	0.54	-4.3	77	260	0.02	S1	*791.3*	*346.6*	*31.5*	438.6	867.8	75	1.4	PEN	0.172	1.000	0.37	0.23	262.4
									S2	*694.5*	*361.9*	*33.9*	465.9	867.8	75	1.4	PEN	0.171	1.000	0.37	0.19	182.3
									S3	*0.0*	--	--	<---	Source is not emitting this hour								
10	20031613	451.9	0.12	0.68	-4.3	117	360	0.025	S1	*544.1*	*357.1*	*31.5*	434.8	1051.4	80	1.5	PEN	0.215	0.603	0.46	0.40	156.4
									S2	*625.8*	*367.8*	*33.2*	442.9	1051.4	80	1.5	PEN	0.215	0.641	0.46	0.39	174.9
									S3	*364.2*	*355.7*	*28.2*	428.9	1051.4	80	1.5	PEN	0.216	0.574	0.46	0.40	105.6

For the hour ending 11 on June 3, 2019, AERMOD reported a penetrated plume at final heights for the three Martin Lake units averaging about 587 m, while the convective mixing height was 485 m (representing the value at the midpoint of the hour). For the following hour, the convective mixing height rose to about 658 m and as a result, the mixing height at the end of hour 11 was still below the three Martin Lake units' plume centerlines at about 572 m. AERMOD assigned large sigma-z values of about 228 – 242 m, resulting in a layer for effective parameters reaching well into the convective mixed layer, down to a level of about 107 m above the ground. **Figure 8, *AERMOD-Simulated Sigma-w as a Function of Height for June 3, 2019, Hour Ending 11,*** shows a plot of the sigma-w profile and the effective turbulence calculations in AERMOD. The sigma-w (green line) is the AERMOD internally calculated sigma-w extracted from the METEOR debug file.

The local value of sigma-w at the penetrated plume centerline shown in **Figure 8,** is about 0.30 m/s. However, the internal AERMOD calculations of the effective sigma-w value created an average sigma-w value of more than twice the centerline value (about 0.63 m/s) in a layer between the plume centerline at ~590 m down to ~105 m. This mixing was applied to the entire mass of the penetrated plume, even though most of it remained above the mixing height even at the end of the hour. The result was an AERMOD prediction at the monitoring site of 244.0 μg/m^3, almost twice the observed value of 123.3 μg/m^3.

For the hour ending 11 on June 29, 2019, AERMOD reported a penetrated plume at final heights for the three Martin Lake units averaging about 390 m, while the convective mixing height was 296 m (representing the value at the midpoint of the hour). For the following hour, the convective mixing height rose only 10 m to 306 m (well under the plume centerline); hence the mixing height at the end of hour 11 was still below the three units' plume centerlines at about 301 m. AERMOD assigned large sigma-z values of about 125 m, resulting in a layer for effective parameters reaching well into the convective mixed layer, down to a level of about 120 m above the ground. **Figure 9, *AERMOD-Simulated Sigma-w as a Function of Height for June 29, 2019, Hour Ending 11,*** shows a plot of the sigma-w profile and the effective turbulence calculations in AERMOD.

The plot in **Figure 9** shows that the local value of sigma-w at the penetrated plume centerline is about 0.20 m/s. However, the internal AERMOD calculations of the effective sigma-w value created an average sigma-w value of 2.4 times the centerline value (about 0.48 m/s) in a layer between the plume centerline at ~395 m down to ~115 m. This mixing was applied to the entire mass of the penetrated plume, although most (if not all) of it remained above the mixing height at the end of the hour. The result was an AERMOD prediction at the monitoring site of 485.8 μg/m^3, well above any single hour's measurement at the monitor over the 3-year period.

The key issue is the deep vertical layer over which the effective vertical mixing parameters, especially sigma-w, are calculated. The overly deep vertical layer extends the averaging well into the convective mixed layer, resulting in an exaggerated large plume depth and an associated high impact at the ground. This feature of the penetrated plume treatment was not anticipated by the AERMIC committee in designing the model. The coding of the model that assigned a neutral value to the temperature lapse rate for computation of the penetrated plume sigma-z for a plume in the stable layer aloft is a detail that may have been introduced by the contractor coding the model, but in any case, this issue escaped notice until recently.

Figure 8: AERMOD-Simulated Sigma-w as a Function of Height for June 3, 2019, Hour Ending 11

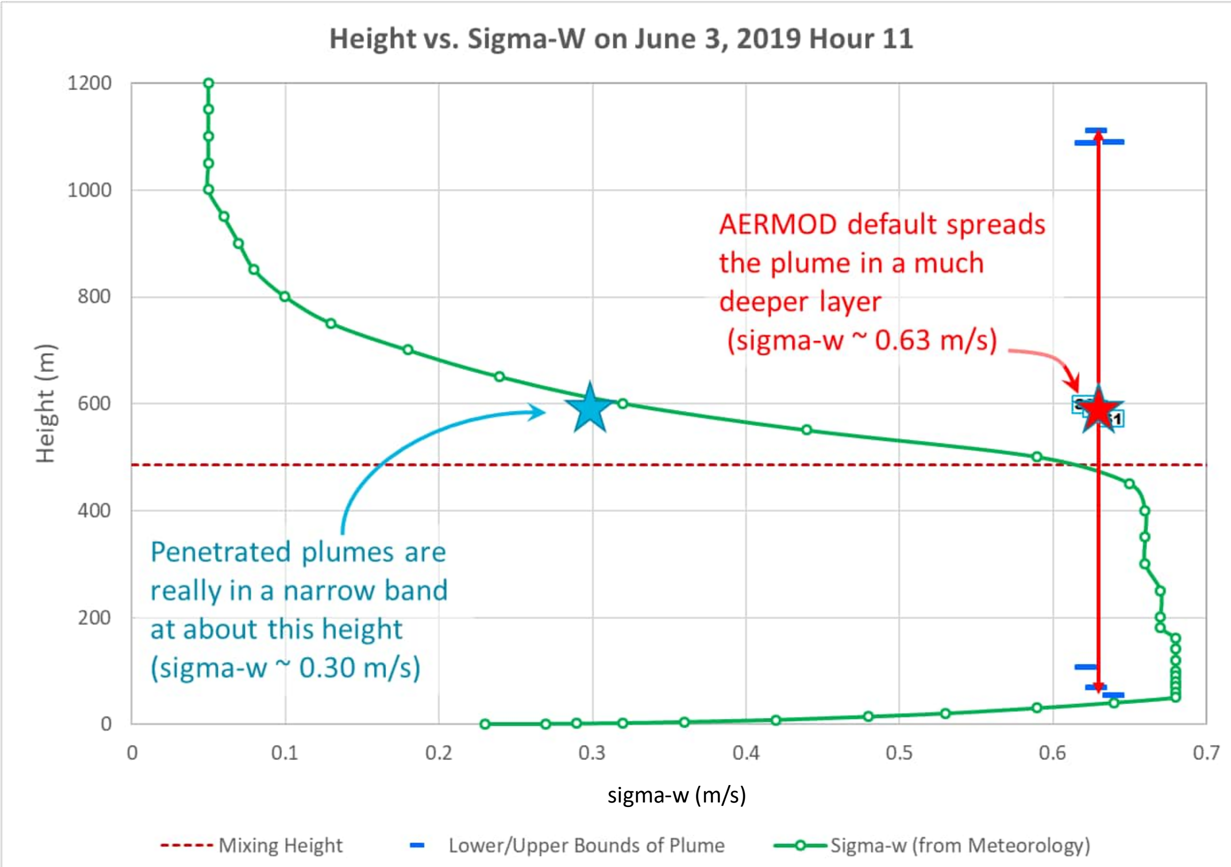
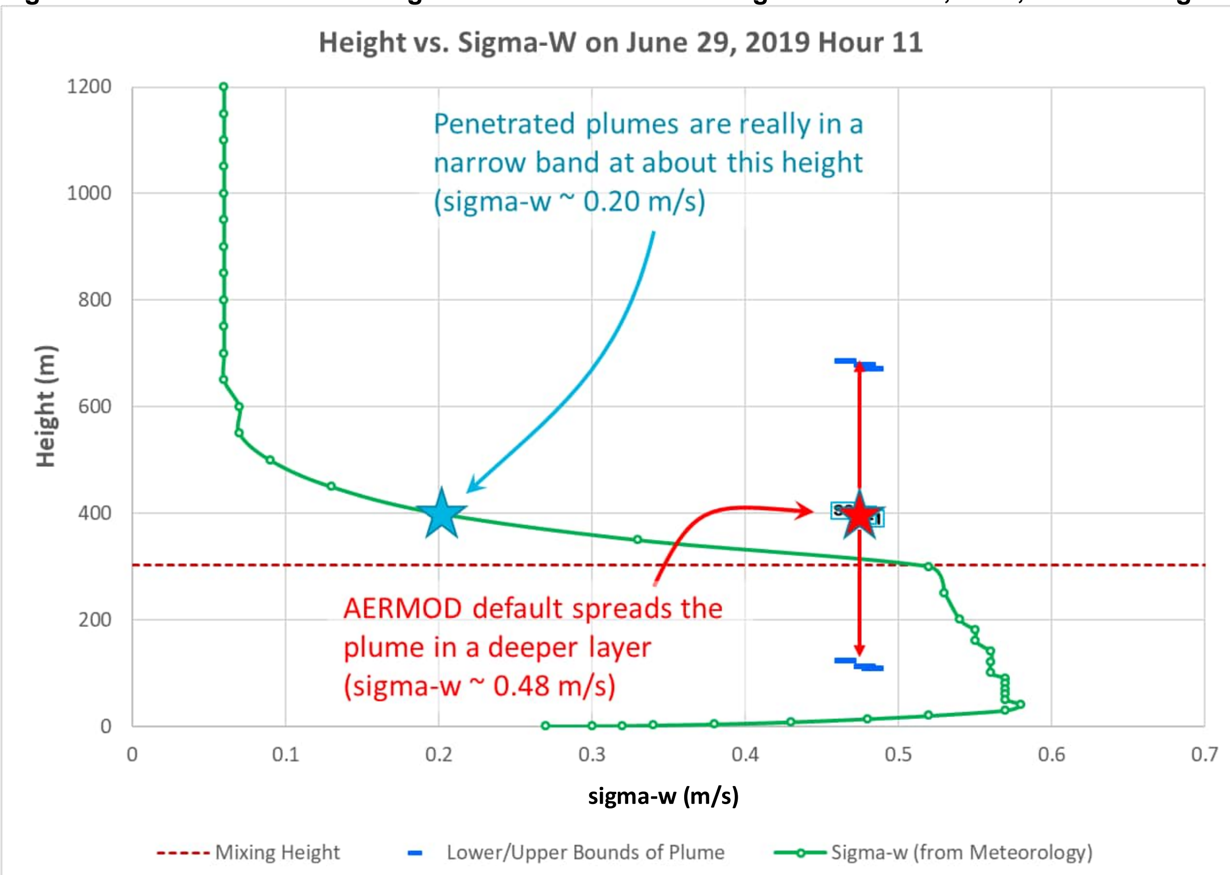


Figure 9: AERMOD-Simulated Sigma-w as a Function of Height for June 29, 2019, Hour Ending 11



Alternative Approach to Penetrated Plume Issue in AERMOD

In the May 2021 modeling package submitted to TCEQ for the modeling of Martin Lake, AECOM utilized an enhancement to AERMOD to address the penetrated plume issue, described above. The enhancement is referred to as the highly buoyant plume or HBP. The enhancement is based in part on a refined approach to characterize the penetrated plume behavior more accurately in AERMOD (Weil 2020). The following sections discuss in detail the formulation of HBP and how it was directly implemented into AERMOD. The version of AERMOD that HBP was initially incorporated to, as part of the May 2021 package to TCEQ, was AERMOD version 21112. This is the same model formulation that EPA has since added to AERMOD version 23132 as their HBP Alpha option (EPA 2023).

HBP has been extensively evaluated on multiple field databases where the penetrated plume issue exists. These evaluations were included as part of a peer-reviewed paper (Warren et al., 2022) in the Journal of the Air and Waste Association.

HBP Formulation in AERMOD

The Gaussian equation for the concentration from the penetrated plume (*Cp*), in both the lateral (x_r and y_r) and vertical directions (where z is either z_r for the horizontal plume state or z_p for the terrain-following state) is given in the current (October 2023) AERMOD Model Formulation Document (MFD) Eqn. 66 by:

$$C_p\{x_r, y_r, z\} = \frac{Q(1-f_p)}{\sqrt{2\pi}\tilde{u}\sigma_{zp}} F_y \cdot \sum_{m=-\infty}^{\infty} \left[\exp\left(-\frac{\left(z-h_{ep}+2mz_{ieff}\right)^2}{2\sigma_{zp}^2} \right) + \exp\left(-\frac{\left(z+h_{ep}+2mz_{ieff}\right)^2}{2\sigma_{zp}^2} \right) \right] \quad (1)$$

where Q is the source emission rate, f_p is the penetrated plume fraction, $\tilde{u}$ is the effective wind speed, σ_{zp} is the total dispersion for the penetrated source, F_y is the total horizontal distribution function (with meander), m is the image source (Weil et al., 1997), h_{ep} is the penetrated source plume height (at centerline) above stack base and z_{ieff} is the height of the upper reflecting surface in a stable layer.

A key deficiency of AERMOD in its treatment of the penetrated plume model is the assumption of a steady-state scenario that does not consider the rate of growth of the convective boundary layer (CBL) during a given hour. As noted below, a recommended approach from Weil et al. (1997) to address the CBL growth by the end of each hour for the penetrated plume dispersion formulation has been implemented into the Highly Buoyant Plume (HBP) modifications to AERMOD.

As noted by Weil et al., (1997), the dispersion of a penetrated plume dispersion is an unsteady process, but it is implemented as a steady process in AERMOD due to the inherent limitations of steady-state models. The current AERMOD formulation for the vertical dispersion of the penetrated plume is based upon Eqn. 83 in the MFD:

$$\sigma_{zes} = \frac{\tilde{\sigma}_{wT}\, t}{\left[1+\frac{\tilde{\sigma}_{wT}\, t}{2}\left(\frac{1}{0.36h_{es}}+\frac{N}{0.27\tilde{\sigma}_{wT}}\right)\right]^{1/2}}. \quad (2)$$

where σ_{zes} is the elevated portion of the ambient dispersion for the stable plume, the effective value of σ_{wT} is the total vertical turbulence, h_{es} is the plume release height, and N is the stable Brunt-Vaisala frequency. However, for the penetrated plume, AERMOD currently (and inappropriately in many cases) assigns a zero value to N, corresponding to a value in the CBL, implying the assumption that the convective mixing height grows to intercept the entire penetrated plume by the end of the hour. However, in many cases, only a fraction of the penetrated plume mass has been entrained into the CBL by the end of the hour, but AERMOD does not currently check for this entrainment. Paine et al. (2019) suggest a modification that limits the AERMOD calculation for the penetrated plume contribution to the ground-level concentration to the extent to which the growing mixed layer $z_i(t)$ has intercepted the penetrated plume, which effectively adopts the fumigation onset as the dispersion trigger.

Weil et al. (1997) in its Eqn. 31 and 32 provide a formulation for the fraction of the plume mass assigned to the penetrated plume portion that has been intercepted by the CBL:

$$f_p = (1 - f)\frac{f_t f_q}{f_d}. \qquad (31)$$

Here, $1 - f$ is the fraction of the source material that is in the penetrated plume, f_d ($\sim$0.6) is the fraction of the w PDF comprised by downdrafts, f_t (=0.5) is the fraction of the hourly period over which the penetrated source contributes to the GLCs, and f_q is the fraction of the penetrated plume that is captured by the growing CBL during the second half of the hour.

The f_q is given by

$$f_q = \min\left(\frac{\tilde{z}_{i2} - h_l}{h_u - h_l}, 1\right), \qquad (32)$$

where $\tilde{z}_{i2} = \tilde{z}_i$ ($t' = 30$ min) is the CBL height at the end of the hour, and h_l and h_u are the lower and upper heights of the penetrated plume (see Fig. 3).

In this formulation, the full penetrated plume mass fraction is *(1-f)*, defined by f_p in the AERMOD formulation. The remaining terms in Eqn. 31 from Weil et al. (1997) are f_q times 0.5/0.6[7], or rounded up to f_q (also referred to as "f_α" in the HBP implementation. Weil et al. assign f_q in their Eqn. 32 to an interpolation of the fractional height of the penetrated plume mass within the CBL. As noted below, the HBP formulation improves upon this interpolation by interpolating the gaussian plume mass within the CBL with the use of the erf function.

The Highly Buoyant Plume (HBP) option, described in detail by Warren et al. (2022), addresses the limitations of AERMOD for handling the penetrated plume's contribution to ground-level concentrations by checking on the convective mixing height for the current hour (assigned to the midpoint of the hour) as well as the next hour to determine how much of the penetrated plume has been captured by the convective boundary layer by the end of the current hour. An average mixing height ($\overline{z_i}$) based on the averaged current and next hour mixing heights is used as a measure of the mixing height at the end of the hour. If three key conditions are met (unstable atmospheric conditions, stack height lower than the mixing height and $f_p > 0$), an entrainment adjustment factor (f_α) is calculated that scales down f_p to mitigate the late morning overpredictions. If these key conditions are met, HBP considers three cases based on the height of the averaged mixing layer with respect to the bottom and top of the penetrated plume (h_{bot} and h_{top}, respectively):

1. IF $\overline{z_i} < h_{bot}$ → $f_\alpha = 0$;
2. IF $\overline{z_i} > h_{top}$ → $f_\alpha = 1$;
3. ELSE → $0 < f_\alpha < 1$

[7] In the explanation of the equation 31 in Weil et al (1997), this fraction is derived from the solution of the vertical velocity PDF where approximately 60% of the PDF is comprised of downdrafts (f_d) and during which 50% of the hourly period (f_t) the penetrated plume contributes to the ground level concentration (GLC).

For the third case, f_α can be obtained by integrating equation 1 over all possible heights yielding a piecewise solution based on the position of the averaged mixing height within the penetrated plume:

$$f_\alpha = \frac{1}{2}\operatorname{erf}\left(\frac{\bar{z}_i - h_{bot}}{\sqrt{2}\sigma_{zp}}\right) \quad \text{for } h_{bot} < \bar{z_i} < h_{ep} \quad (3a)$$

$$f_\alpha = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{\bar{z}_i - h_{ep}}{\sqrt{2}\sigma_{zp}}\right)\right] \quad \text{for } h_{ep} < \bar{z_i} < h_{top} \quad (3b)$$

where erf is the error function. The error function is used to evaluate the area under the curve of the integrated equation 1 to obtain a percentage of the mass entrained within the averaged mixed layer.[8]

With f_α calculated, the contributions from the entrained penetrated plume ($C_{p\alpha}$) can be determined:

$$C_{p\alpha}\{x_r, y_r, z_r\} = f_\alpha C_p \quad (4)$$

Finally, the total concentration in the CBL (C_C) can be evaluated:

$$C_c\{x_r, y_r, z_r\} = C_d\{x_r, y_r, z_r\} + C_r\{x_r, y_r, z_r\} + C_{p\alpha}\{x_r, y_r, z_r\} \quad (5)$$

where C_d and C_r are the contributions from the direct and indirect sources, respectively. Note that the entrainment adjustment factor is only used to adjust the penetrated plume and does not affect the direct or indirect components of the plume.

Implementation of HBP in AERMOD

This section provides a more qualitative explanation of the HBP approach. HBP as illustrated in the flowchart shown in **Figure 10, Flowchart for Highly Buoyant Plume**, involves a check on the convective mixing height for the current hour as well as the next hour to determine how much of the penetrated plume has been captured by the convective boundary layer by the end of the current hour. The amount of the penetrated plume mass that is allowed to mix to the ground in HBP depends upon the result of this calculation. If three key conditions are met (unstable atmospheric conditions, stack height lower than the mixing height and f_p > 0), there are three possible outcomes.

Case 1: No penetrated plume impact. If the average of the current and the next hour's convective mixing height (each value represents the half-hour mark,[9] so the average is roughly at the end of the current hour) is below the bottom of the penetrated plume final height, then no portion of the penetrated plume is assumed to mix into the convective boundary layer. In that case, the contribution of the penetrated plume mass at the receptor is assumed to be zero. The "bottom" of the penetrated plume is 2.15σ_z below the plume centerline height, where the concentration drops to 10% of that at the plume centerline (with a Gaussian distribution assumed).

Case 2: Full penetrated plume impact. If the mixing height at the end of the current hour is above the top of the penetrated plume, then the full mass of the plume is assumed to reach the ground, and the current AERMOD formulation is used for that hour.

Case 3: Partial (entrained) penetrated plume impact. For convective mixing heights (by the end of the current hour) that are in between the bottom and top of the penetrated plume, a fraction of the plume mass computed using a vertical Gaussian distribution is assumed to reach the ground using the current AERMOD formulation. For example, the captured fraction is 0.5 if the mixing height at the end of the current hour is exactly at the penetrated plume centerline. If the mixing height at the

[8] In Weil et al. (1997), Eq. 32 provides a linear equation for defining the entrainment adjustment factor. However, by integrating the Gaussian penetrated plume equation (Eq. 1) and using the error function, a more refined solution can be determined based on a Gaussian bell-shaped cross section of mass rather than a step-function uniform cross section (i.e., "top hat" shape) for which the linear f_α is a solution.

[9] Ibid. states (p. 988) that "Penetrated source material is assumed to be mixed into the CBL [convective boundary layer] only when the growing, time dependent CBL height $\bar{z} > \bar{z_i}$, where $\bar{z_i}$ is the average mixed layer depth over the hour and is representative of the midpoint of the hour."

end of the hour is below (or above) the penetrated plume centerline height, then less (or more) than half of the mass of the penetrated plume will be mixed to the ground.

The approach implemented in HBP is straightforward, and the resulting plume behavior is consistent to what is seen in research-grade experiments (Warren et al., 2022). The approach also extends AERMOD's capability for dealing with only one hour at a time by enabling it to determine the rate of change for the convective mixing height, with the possibility that the rising mixing height could intercept at least part of the penetrated plume in the current hour. HBP only affects AERMOD during the critical period of the late morning / early afternoon when the rise of the convective mixing height into the layer containing the penetrated plume is demonstrated to occur; at all other hours, HBP is equivalent to AERMOD run with default options.

The key conditionals (i.e., unstable atmosphere, stack height below mixing height and non-zero penetrated plume fraction, noted as PPF in the code) as well as the aforementioned three cases were coded into the IBLVAL subroutine[10] within the iblval.f Fortran module. Annotations (in **bold**) to the code below have been added that directly point to the key conditionals as well as the three cases for defining the entrainment adjustment factor (noted as PPFN in the code). The noted line numbering is in reference to the submitted AERMOD version 21112. Comments in the code have been removed to focus solely on the code. The full code modifications associated with HBP are included as **Attachment 3** to this document, which are identical to what was provided to TCEQ in May 2021 for its SIP submittal.

SUBROUTINE IBLVAL (in iblval.f)

Key conditionals:

1. **Unstable atmosphere (line 310);**
2. **Stack height lower than mixing height (line 310) and;**
3. **Partial Penetration Fraction (PPF) > 0 (Line 317)**

If all 3 conditions are true, the subsequent calculation of the entrainment adjustment factor (PPFN) is performed. If any of those 3 conditions are false, the PPFN conditional block below is skipped and PPF is used as-is.

```
Line 310      ELSE IF (UNSTAB .AND. (HS.LT.ZI)) THENLine 317          IF( PPF .GT. 0.0D0 )THEN
```

Conditional block for assessing varying cases for calculating PPFN.

Calculate the height of the penetrated plume top (HHTOP) and bottom (HHBOT). The distance from the centerline of the penetrated plume (HE3) to the region where the concentrations drop to 10% from those at the center is $2.15\sigma_z$.

```
Line 322              HHTOP = HE3 + 2.15D0*SZ3  ! top of plume
Line 323              HHBOT = MAX(HE3 - 2.15D0*SZ3,ZRT)  ! Bottom of plume
```

The penetrated plume width (PPWID) is calculated along with the difference in height between the top of the plume and the end-of-hour mixing height (ZIAVG).

```
Line 325              PPWID = HHTOP - HHBOT
Line 327              HTOPDIF = HHTOP – ZIAVG
```

Start of the PPFN Conditional Block for the selecting which of the 3 Cases to use for calculating PPFN.

Assess the difference in height between top of the plume and the mixing height at the end of the hour is positive (i.e. if the top of the plume is above the end-of-hour mixing height).

```
Line 328            IF (HTOPDIF .GT. 0.0D0) THEN
```

If the difference is positive, then assess if the difference is less the penetrated plume width (i.e. if the end-of-hour mixing height is within the plume).

```
Line 330         IF(HTOPDIF .LT. PPWID) THEN
```

[10] The IBLVAL subroutine calculates the effective parameters in the Inhomogenous Boundary Layer

If the end-of-hour mixing height is within the plume, Case 3 is selected with the next step is determining whether to use Equation 3a or 3b from the HBP model formulation for calculating PPFN. Assess if the end-of-hour mixing height is less than the penetrated plume centerline (i.e. if the end-of-hour mixing height is in the lower half of the penetrated plume).

```
Line 331          IF(ZIAVG .LE. HE3) THEN
```

If the end-of-hour mixing height is in the lower half of the penetrated plume then Equation 3a is selected which will yield a value of PPFN between 0 and 0.5.

```
Line 334           PPFN = 0.5D0*ERF((ZIAVG-HHBOT)/SZ3/DSQRT(2.0D0))
```

If the end-of-hour mixing height is within the penetrated plume but not in the lower half use Equation 3b which yields a value of PPFN greater than 0.5 and less than 1

```
Line 335          ELSE
Line 338           PPFN = 0.5D0*(1.0D0 +
Line 339      &                       ERF((ZIAVG-HE3)/SZ3/DSQRT(2.0D0)))
Line 340          ENDIF
```

However, if the top of the penetrated plume is above the end-of-hour mixing height but is not within the penetrated plume, then the end-of-hour mixing height is determined to be below the bottom of the plume and PPFN is set to 0 (Case 1).

```
Line 341        ELSELine 344         PPFN = 0.0D0
Line 345        ENDIF
```

However, if the top of the penetrated plume is below the end-of-hour mixing height then the entire penetrated plume is entrained within the convective mixing layer and PPFN is set to 1 (Case 2) and hence PPF is used as-is.

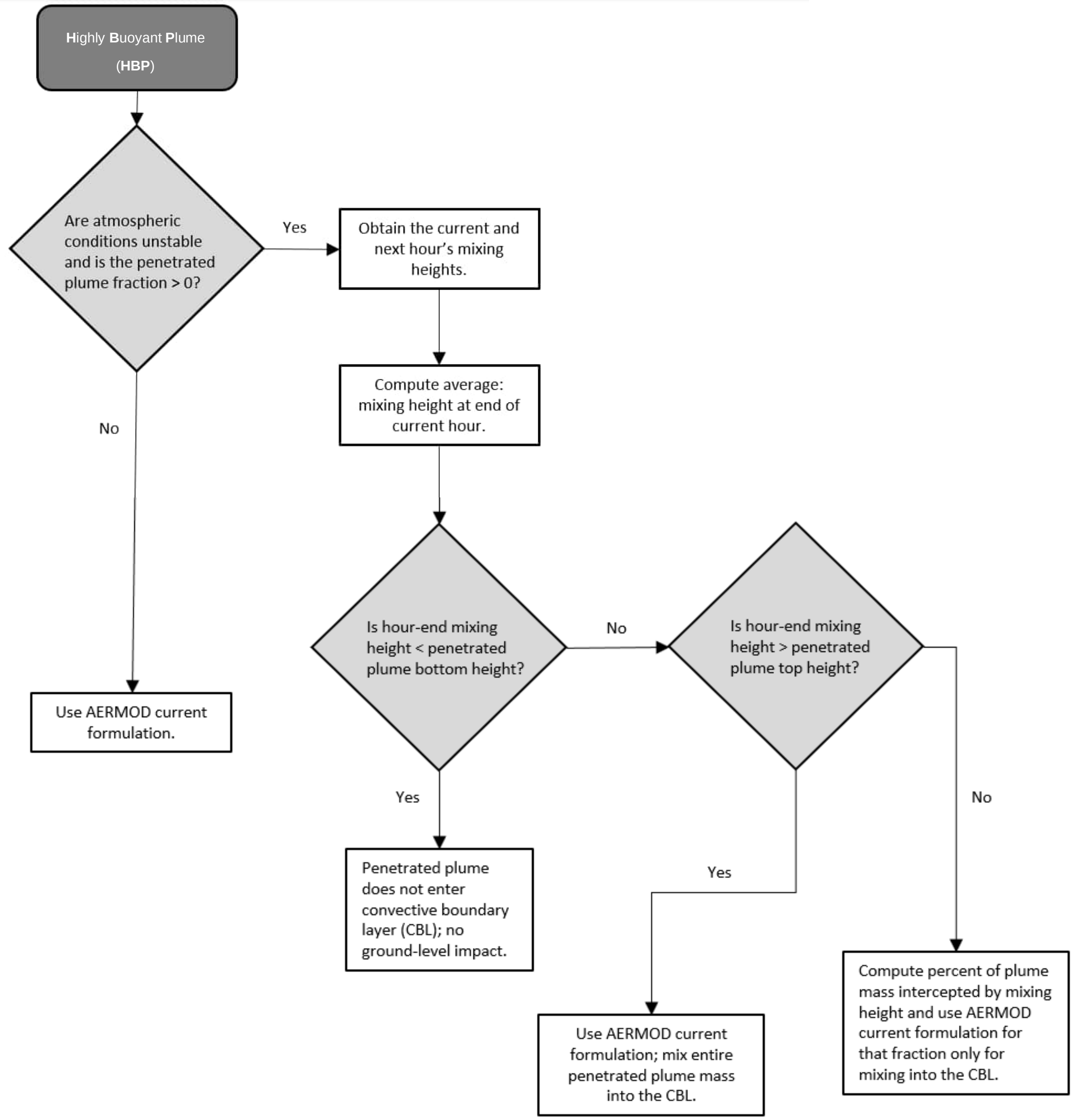
```
Line 346      ELSE
Line 347        PPFN = 1.0D0
```

End the PPFN conditional block and save the penetrated σ_z for the optional debug file.

```
Line 348      END IF
Line 349      SZ3DBG = SZ3
```

Attachment 4 contains a PDF of example hand-calculations from a submitted spreadsheet (*Spreadsheet for calculating PPFN v5.xlsx)* for each of the case discussed.

Figure 10: Flowchart for Highly Buoyant Plume



Summary

At the request of EPA, this document provides in-depth information on the model formulation of HBP to support a site-specific model for Martin Lake. The formulation and implementation of HBP in AERMOD has remained unchanged from what was previously provided by TCEQ to EPA in support of its Appendix W request in May 2021. As explained in TCEQ's submission, and as further supported by this additional information requested by EPA, TCEQ's request meets all the requirements for an alternative model as provided in 40 CFR Part 51, Appendix W, and it should be approved by EPA.

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Attachment 1: Plume Behaviors Observed Using LIDAR and SF_6 Tracer at a Flat and Hilly Site

Attachment 2: Distance-Debug and HRBINARY: Modeling Tools for Unpacking the AERMOD Blackbox

This document included copyrighted material that has been removed. The following documents were removed and available to view at EPA Region 6 office.

Moore, G .E., Milich, L .B., Liu, M. K., 1988: Plume Behaviors Observed Using Lidar and SF_6 Tracer at a Flat and Hilly Site. Atmospheric Environment Vol. 22, No. 8, pp. 1673-1688

DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD BlackBox

A&WMA Annual Conference and Exhibition

Pittsburgh, PA

June 5-8, 2017

Abstract # 298000

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The business of sustainability

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DISTANCE-DEBUG and HRBINARY: Modeling Tools for Unpacking the AERMOD BlackBox

AERMOD, the U.S. Environmental Protection Agency preferred air dispersion model, is a steady-state model that incorporates concepts of planetary boundary layer turbulence with plume dispersion dynamics. The model statistically approximates horizontal and vertical plume transport interacting with hourly meteorology, terrain and any identified impact from building downwash and urban enhanced buoyancy. An array of pre-processors generates meteorological, topographic and building downwash inputs for AERMOD. These inputs allow AERMOD to calculate hourly ground level concentration gradients.

Despite the quality of the inputs, assumptions or faulty implementation within a model's formulation can potentially generate questionable or even erroneous results. While there are several debugging options for investigating AERMOD's intermediary calculations, these current options produce massive cumbersome output files unless run on a single receptor or single hour. The Electric Power Research Institute (EPRI) sponsored a study to develop a model tool, "DISTANCE-DEBUG" that would efficiently diagnose causes for predicted high concentrations. DISTANCE-DEBUG generates a streamlined hourly file echoing key meteorology and tabulating AERMOD-calculated plume dynamics for each point, volume and area source. Hourly intermediary concentration calculations are also reported for the coherent plume. Example cases will be presented that highlight the DISTANCE-DEBUG features, particularly its legibility and ease of use.

A separate EPRI-funded tool, "HRBINARY", in conjunction with a concentration processor ("BINMERGE-2017") will be discussed that allows for binary output from multiple AERMOD runs to be post-processed, including an example case of two buoyant line sources using different buoyancy parameters, an option not currently available in AERMOD version 16216r.

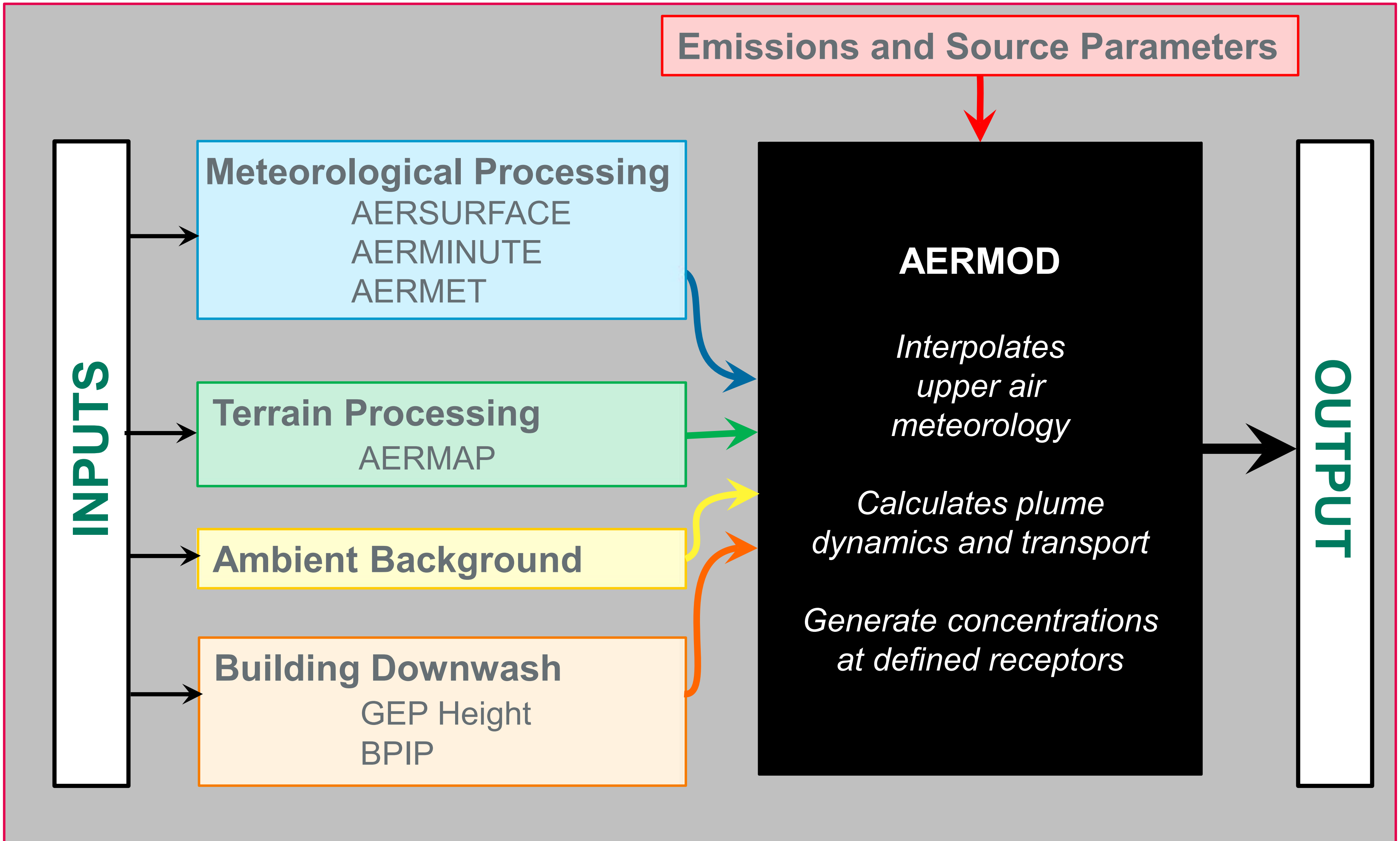
Overview

In 2012, the Electric Power Research Institute (EPRI) sponsored two modeling tools:

- **DISTANCE-DEBUG** an AERMOD debugging tool intended to streamline the diagnostics associated with predicted high concentrations.

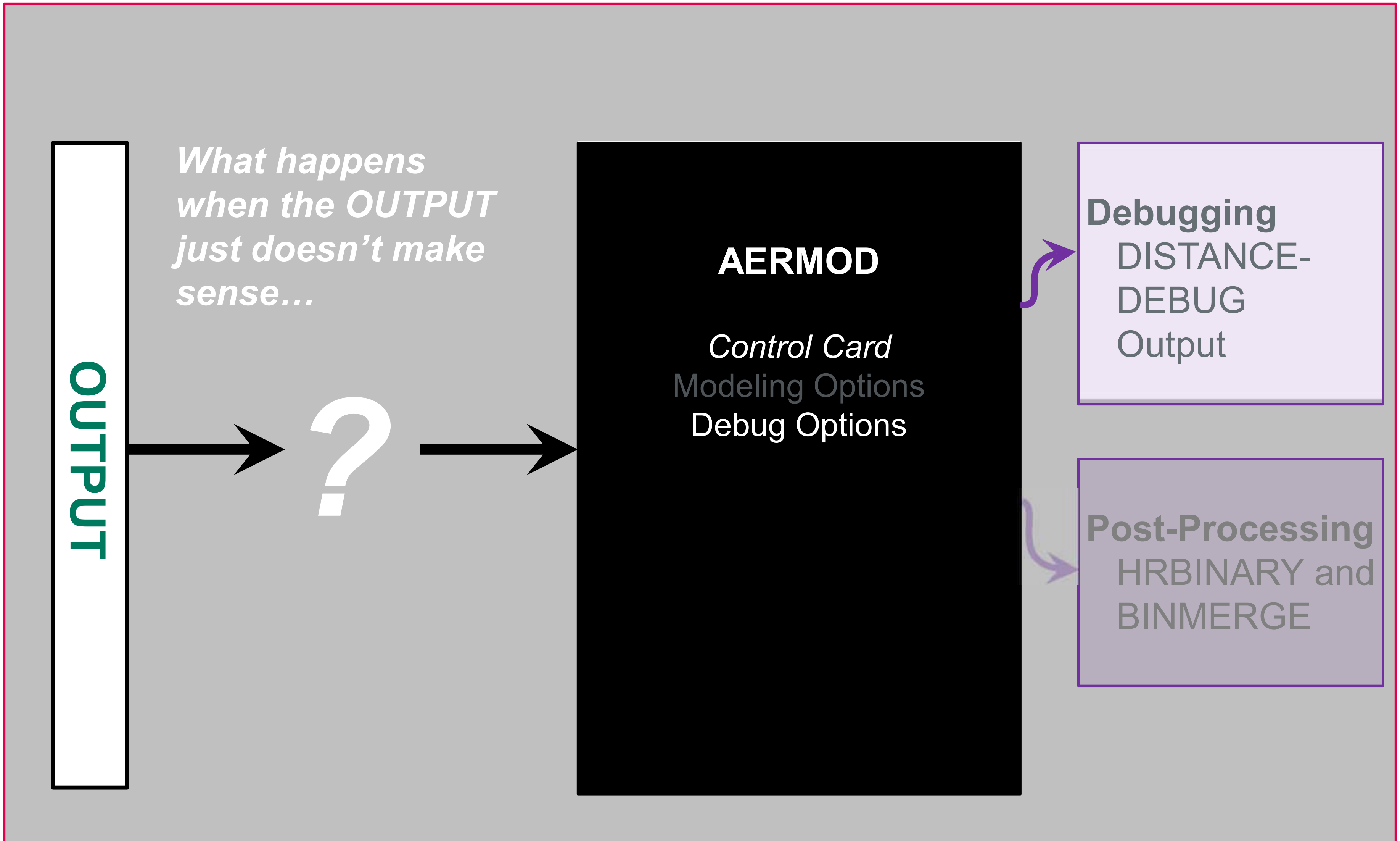
- **HRBINARY,** a post-processing option in AERMOD that (in conjunction with another post-processor, “BINMERGE”) allows for merged output from multiple (but separately performed) AERMOD runs to be analyzed to generate NAAQS-ranked design value output.

The AERMOD BlackBox



AECOM ERM

The AERMOD BlackBox



Debugging…so many options

- **MODEL:** General modeling debug file
- **METEOR:** General meteorological
- **PRIME:** PRIME downwash
- **DEPOS:** Deposition (for both gas & particle)
- **AREA or LINE:** Area, Line and Open Pit
- **PVMRM or OLM or ARM or ARM2:** NO_x-to-NO_2 conversion

So why the need for <u>another</u> debug file?

…can be overwhelming

Excerpt from 60,000 line PRIME Debug file

```
PRIME Module Results for Current Source and Hour
           (all lengths in meters)
 ------------------------------------------------

     XB       X       Z   Hwake    Hcav     Sz      Sy    Ufac  dUfac  R->Sz   dRdx  Pos  Szcav  Sycav

    48.5     0.0    42.7   74.9    49.6     0.0     0.0  0.639  0.000    0.0  0.000    1   14.2   34.5
    48.5     0.0    43.7   74.9    49.6     0.3     0.3  0.638  0.000    1.6  0.000    1   14.2   34.5
.
.
.
   970.2   921.8    47.0  182.7     0.0    66.8    86.9  0.832  0.001   47.2  0.038    3   65.1  109.4
  1008.2   959.8    46.6  185.0     0.0    67.8    88.3  0.835  0.001   47.2  0.003    3   66.2  111.1

 YR/MN/DY/HR:         10070101   ISRC:            1   IREC:            1

  GAMFACT =   6.940565230893733E-004
  AERVAL  =    5.69810811953800
  PRMVAL  =    121.518405396800
  HRVAL   =    5.77849395236943

 YR/MN/DY/HR:          10070101

 WAKE_SCALES inputs:
    HB    =    49.6200000000000       (m)
    WB    =    86.5100000000000       (m)
    LB    =    112.940000000000       (m)

 WAKE_SCALES output:
    Scale length (R)              =    59.7209366698920
    Max. cavity height (HR)       =    62.7586060673762
    Length of downwind cavity (LR) =   85.7776606883091
    Length of roof cavity (LC)    =    53.7488430029028
 PRIME Effective Parameters:
 ZLO, ZHI     =   0.500000000000000        178.035578770569
 SWEFF, SVEFF =   0.168846389190163       0.343228206052833
 UEFF,  TGEFF =    6.86456412105667       5.997118404810090E-002
```

…can be overwhelming (cont'd.)

Excerpt from 60,000 line PRIME Debug file

```
NNP        X      Y      Z      R      U      V      W     USC     PHI    DEN    TP      UA     RA     TA      DUDZ    DPDZ   DZDS    DYDS IPOS DELTAZ
     1    0.08   0.00  47.62   2.61   1.78   0.00   9.65   9.82  1.3887 1.090 312.02   5.57  1.180 288.37   0.057   0.070  0.000  0.000    1  0.994
     2    0.35   0.00  48.58   3.47   2.84   0.00   7.02   7.58  1.1862 1.114 305.41   5.63  1.179 288.42   0.056   0.070  0.000  0.000    1  1.953
     3    0.80   0.00  49.47   4.27   3.50   0.00   5.42   6.45  0.9974 1.129 301.38   5.67  1.179 288.48   0.056   0.069  0.000  0.000    1  2.839
     4    1.40   0.00  50.27   4.97   3.93   0.00   4.41   5.91  0.8423 1.138 298.83   5.73  1.179 288.53   0.102   0.069  0.000  0.000    3  3.635
     5    2.11   0.00  51.36   5.54   4.25   0.00   3.73   5.66  0.7212 1.144 297.15   5.81  1.178 288.59   0.103   0.069  0.387  0.000    3  4.730
     6    2.88   0.00  52.39   6.01   4.48   0.00   3.27   5.54  0.6300 1.149 295.99   5.89  1.178 288.65   0.105   0.069  0.399  0.000    3  5.759
     7    3.71   0.00  53.35   6.41   4.66   0.00   2.93   5.50  0.5609 1.152 295.16   5.96  1.178 288.71   0.106   0.069  0.393  0.000    3  6.716
     8    4.57   0.00  54.23   6.76   4.80   0.00   2.67   5.49  0.5074 1.154 294.53   6.02  1.177 288.76   0.107   0.069  0.376  0.000    3  7.604
     9    5.45   0.00  55.06   7.07   4.91   0.00   2.46   5.50  0.4649 1.156 294.03   6.08  1.177 288.81   0.109   0.069  0.354  0.000    3  8.429
    10    6.35   0.00  55.83   7.35   5.01   0.00   2.30   5.51  0.4304 1.157 293.64   6.13  1.177 288.85   0.110   0.069  0.331  0.000    3  9.196
    11    7.26   0.00  56.54   7.61   5.09   0.00   2.16   5.53  0.4016 1.159 293.31   6.17  1.176 288.90   0.111   0.069  0.307  0.000    3  9.910
    12    8.19   0.00  57.21   7.86   5.16   0.00   2.04   5.55  0.3773 1.160 293.03   6.21  1.176 288.94   0.113   0.069  0.283  0.000    3 10.575
    13    9.12   0.00  57.83   8.10   5.21   0.00   1.94   5.56  0.3565 1.160 292.79   6.24  1.176 288.97   0.114   0.069  0.260  0.000    3 11.196
    14   10.06   0.00  58.41   8.32   5.27   0.00   1.85   5.58  0.3385 1.161 292.58   6.27  1.176 289.01   0.115   0.069  0.237  0.000    3 11.776

NUMRISE call to WAKE_DFSN
x,y,z,z+zcum:     10.05785       0.00000      55.07828      58.40623
ds,u,w      :      1.00000       5.26501       1.85351
xb,phi      :     18.14785       0.33849
szi,syi     :      2.42068       2.46556

WAKE_XA Calculations:
ambiz,  ambiy  =   2.459681142350115E-002  5.000000000000001E-002
farizt, fariyt =   3.197585485055150E-002  6.500000000000002E-002
xaz,    xay    =    1008.75405004838        1008.75405004838

----- WAKE_DFSN:        NWAK =           50
Z-dispersion reaches ambient at:    1000.66405004838
Y-dispersion reaches ambient at:    1000.66405004838
xadj, yadj, xi  (m) =         -8.09000        -3.10000        18.14785
xbc, distc, xdc (m) =        112.94000       104.85000       198.71766
lwak,  nws,  npw    =  T           0          497
lcav,  ncs,  npc    =  T          48
```

DISTANCE-DEBUG: Focus on Clarity

```
* * * * * * * AERMOD DISTANCE DEBUG FILE * * * * * * *

PLUME TYPES:
  GAUSSIAN:    Idealized plume under stable conditions or when the stack height > the mixing
               height under unstable conditions
  DIRECT:      Direct transport of plume material to the ground within the mixed layer
  INDIRECT:    Portion of the plume caught in convective updrafts but does not penetrate elevated
               inversions. The indirect plume material eventually is reflected down to the ground.
  PENETRATED:  Portion of the plume that penetrates the elevated inversion and is eventually
               re-entrained into the CBL (Convective Boundary Layer)

OTHER TERMS USED:
  MEAND FRAC: Meander fraction (m.f.); the fraction of the total concentration component associated with
               the meander component. The remaining fraction is assigned to the coherent component.
  PART PEN FRAC: Partial penetration fraction
  HRVAL:       Overall calculated hourly concentration; HRVAL = (1-GAMFACT)*AERVAL + (GAMFACT*PRMVAL)
                                                where AERVAL = m.f.*PANCAKE + (1 - m.f.)*COHERENT
                                   For volume sources: HRVAL = (1-m.f.)*AERVAL + (m.f.)*PANCAKE
                                   For area sources:   HRVAL = AbsoluteValue(VAL)*QTK*EMIFAC
  AERVAL:      Portion of hourly concentration not associated with downwash
  PRMVAL:      Portion of hourly concentration associated with downwash
  GAMFACT:     Gamma Factor; scaling factor associated with the PRMVAL
  PANCAKE:     Value from calculating a *pancak-ing* plume
  COHERENT:    The coherent portion of the plume NOT associated with downwash
  VAL:         Iterated integral hourly concentration for an area source
  QTK:         Adjusted emission rate factor
  EMIFAC:      Emission rate unit factor

****************************************************************************************************
NOTES:     [1] The urban Monin-Obukhov length, URB_OBULEN, and the urban mechanical mixing height, ZI_URB,
               are displayed for only the first urban source group.
           [2] GAMFACT & PRMVAL marked with:
               PLUME OUT OF WAKE designates no downwash due to the plume being outside the wake zone
               RCPTR OUT OF WAKE designates no downwash affect at the maximum receptor
           [3] Hourly values and receptor numbers listed are for the MAXIMUM CONCENTRATION calculated
               for each source.
           [4] The potential temperature gradient listed is at the stack height.
           [5] Final plume height, effective windspeed (ueff), and the effective sigma v and w values
               are provided for only the COHERENT portion of the plume.
               The values associated with the MEANDER component are not listed.
           [6] A less-than sign, <, is inserted at column 62 for events when ueff would not transport
               the plume for a given source in one hour to the distance of the maximum receptor.
```

DISTANCE-DEBUG:

Each file begins with a legend of the extracted parameters

Some parameters are only reported for the **coherent plume** (versus the meander component of the plume)

DISTANCE-DEBUG Output

Basic met hourly met data

OBSERVED MET CONDITIONS FOR:	USTAR	WSTAR	OBULEN	URB_OBULEN	ZIMECH	ZICONV	ZI_URB	SFCZ0	THSTAR
YYMMDDHH: 12040102	(m/s)	(m/s)	(m)	(m)	(m)	(m)	(m)	(m)	(K)
	0.13	-9.00	12.90	N.A.	103.00	-999.00	N.A.	0.4280	0.090

Followed by point source data

POINT SOURCES:

	SOURCE ID	RCPT NO.	FINAL PLUME HT. (m)	DIST. FINAL PL.HT (m)	WDIR FINAL HT. (deg)	Effect. WSPD (m/s)	<------ DISTANCE 3600* ueff (m/s)		TO RECEPT (m)	PLUME TYPE	-----> MEAND. FRAC.	PART. PEN. FRAC.	EFFECT. SIGMA_V (m/s)	EFFECT. SIGMA_W (m/s)	HOURLY CONC. (µg/m3)	AERVAL (µg/m3)	COHERENT (µg/m3)	PANCAKE (µg/m3)	GAMFACT	PRMVAL (µg/m3)	POT. TEMP. GRAD. (K/m)
P	MERGE001	329	153.1	269.4	273.	2.669	9610.1		3242.0	GAU	0.025	0.000	0.200	0.052	35.017	0.000	0.000	0.000	PLUME OUT	OF WAKE	0.01637
	MERGEN01	<--- Source is not emitting during this hour																			
P	POINT002	1130	31.5	172.3	273.	1.347	4848.7	<	9157.9	GAU	0.090	0.000	0.200	0.074	2.209	2.209	2.422	0.066	PLUME OUT	OF WAKE	0.01637
P	POINT003	329	14.4	158.4	273.	1.347	4848.7		3202.3	GAU	0.073	0.000	0.200	0.074	13.187	13.019	14.021	0.330	1.000	13.187	0.01278
P	POINT004	1099	30.6	172.3	273.	1.347	4848.7	<	8260.8	GAU	0.085	0.000	0.200	0.074	2.880	2.880	3.141	0.055	0.000	6.682	0.01278
P	POINT005	325	16.2	158.4	273.	1.347	4848.7		2779.5	GAU	0.070	0.000	0.200	0.074	15.001	15.001	16.095	0.397	0.000	39.017	0.01278
P	POINT006	332	14.6	158.4	273.	1.347	4848.7		3637.3	GAU	0.077	0.000	0.200	0.074	14.365	14.365	15.528	0.358	0.000	24.576	0.01278
P	POINT007	333	15.6	158.4	273.	1.347	4848.7		3690.4	GAU	0.077	0.000	0.200	0.074	14.284	14.284	15.448	0.354	0.000	23.986	0.00781

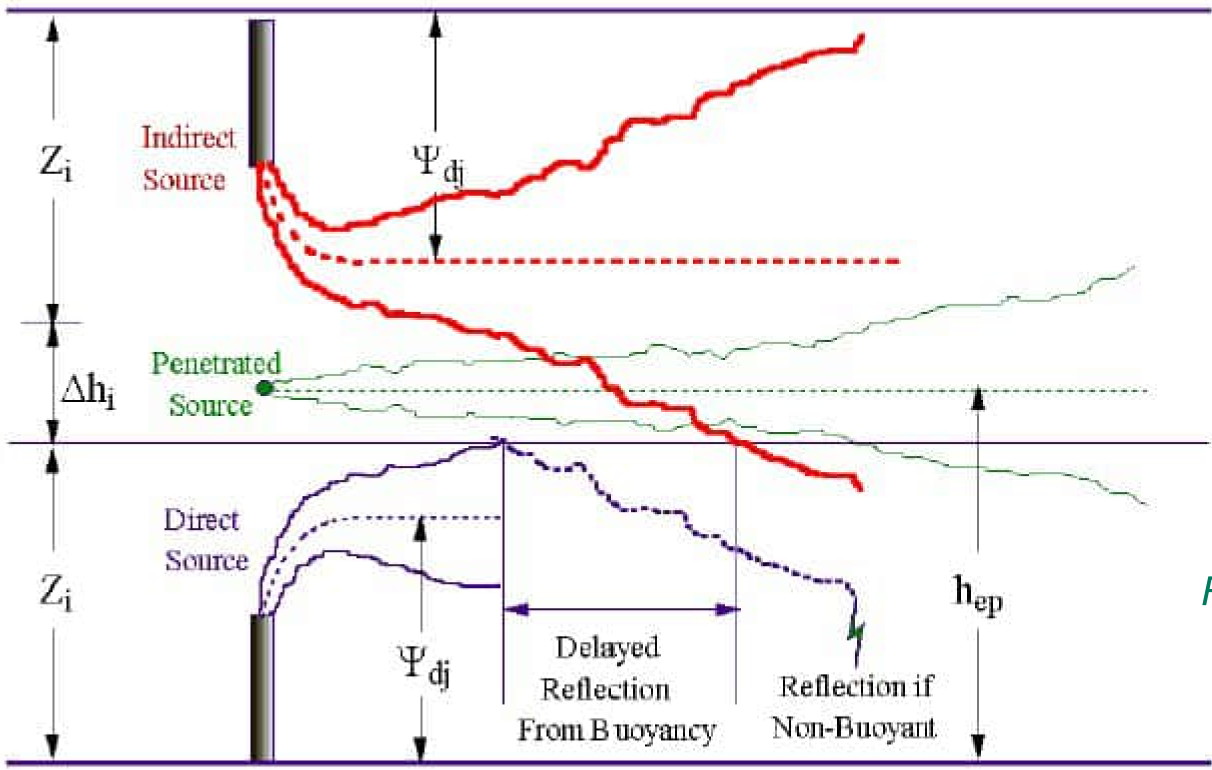
For each source DISTANCE-DEBUG marks predicted max impacts too distant to be reached by the effective wind speed

VOLUME AND AREA SOURCES:

	SOURCE ID	RCPT NO.	FINAL PLUME HT. (m)	DIST. FINAL PL.HT (m)	WDIR FINAL HT. (deg)	Effect. WSPD (m/s)	<------ 3600* ueff (m/s)		RECEPT	TYPE					VAL	(µg/m3)	QTK	EMIFAC
	VOLUME01	<--- Source is not emitting during this hour																
V	VOLUME02	1105	45.0	0.0	273.	2.669	9610.1	<	14473.7	DIR	0.083	0.200	0.052	0.002	0.002	0.000	N.A.	N.A.
	VOLUME03	<--- Source is not emitting during this hour																
V	VOLUME04	1105	45.0	0.0	273.	2.669	9610.1	<	14255.1	DIR	0.082	0.200	0.052	0.002	0.002	0.000	N.A.	N.A.
	VOLUME05	<--- Source is not emitting during this hour																
V	VOLUME06	328	5.0	0.0	273.	0.929	3344.9		3055.8	DIR	0.222	0.200	0.079	0.507	0.648	0.017	N.A.	N.A.
	VOLUME07	<--- Source is not emitting during this hour																
V	VOLUME08	1090	35.0	0.0	273.	2.539	9141.4	<	14347.0	DIR	0.114	0.200	0.054	0.025	0.029	0.001	N.A.	N.A.
	VOLUME09	<--- Source is not emitting during this hour																
V	VOLUME10	324	5.0	0.0	273.	0.929	3344.9		2681.8	DIR	0.217	0.200	0.079	0.634	0.804	0.021	N.A.	N.A.
A	AREA01	325	10.0	0.0	273.	1.347	4848.7		3427.0	DIR	N.A.	0.200	0.074	236.915	0.237E+00	N.A.	0.1E-02	0.1E+07

AECOM ERM

Example of Reported Point Source Parameters



← Mixing Height, z_i
z_{conv}, z_{mech} or z_{urb}

Final plume height (centerline)
$\psi_{dj} = H_s + H_p$

Not shown:
Gaussian plume: idealized plume under stable conditions or during unstable conditions when stack height > mixing height

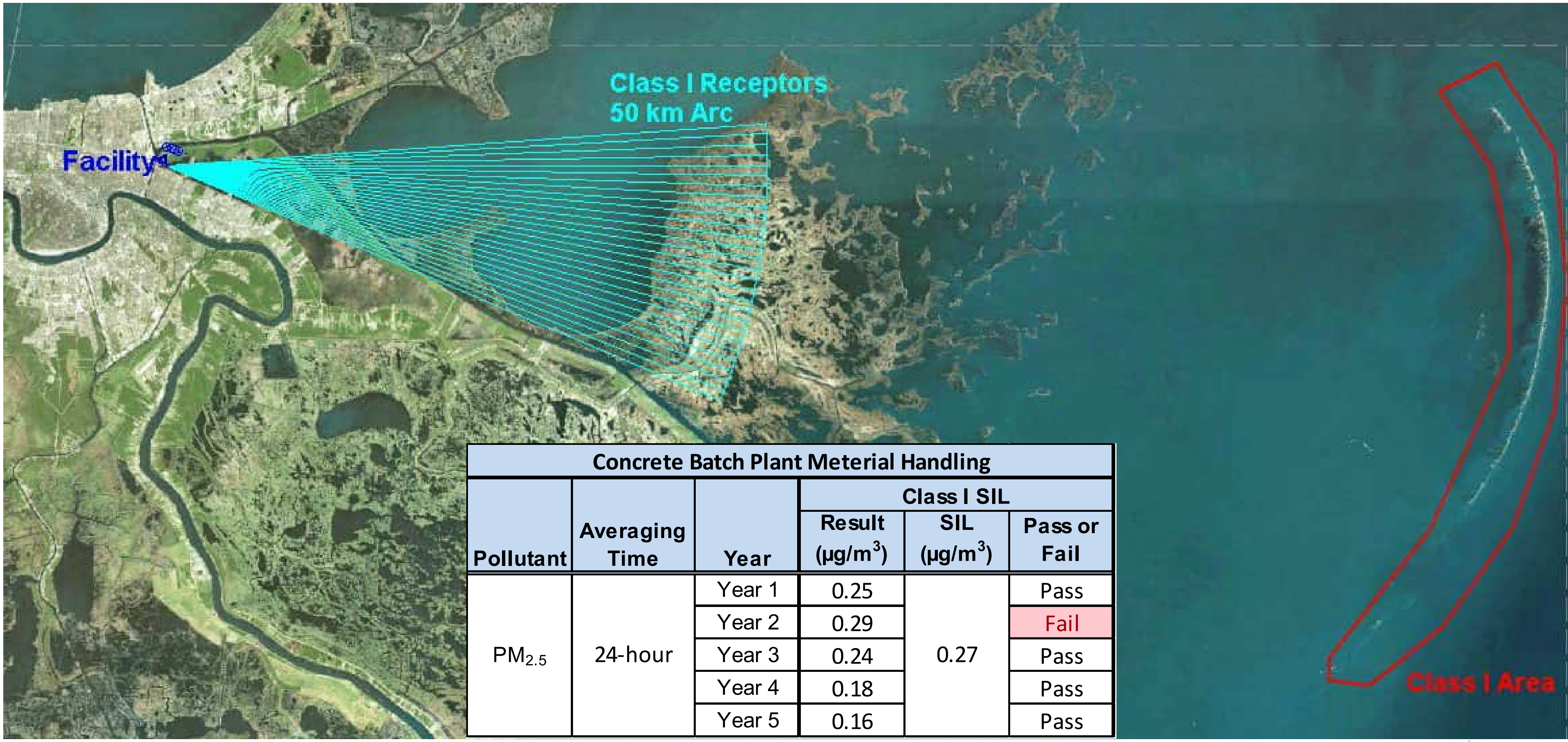
DISTANCE-DEBUG Output

```
OBSERVED MET CONDITIONS FOR:  USTAR  WSTAR  OBULEN  URB_OBULEN  ZIMECH  ZICONV   ZI_URB   SFCZ0   THSTAR
YYMMDDHH: 12040102            (m/s)  (m/s)  (m)     (m)         (m)     (m)      (m)      (m)     (K)
                               0.13  -9.00  12.90        N.A.   103.00  -999.00  N.A.     0.4280   0.090
--------------------------------------------------------------------------------------------------------

POINT SOURCES:
  SOURCE        RCPT   FINAL  DIST.  WDIR   Effect. <------ DISTANCE -----> MEAND. PART.  EFFECT.  EFFECT.  HOURLY                                                     POT.
  ID            NO.    PLUME  FINAL  FINAL  WSPD    3600*      TO    PLUME  FRAC.  PEN.   SIGMA_V  SIGMA_W  CONC.    AERVAL   COHERENT  PANCAKE  GAMFACT  PRMVAL    TEMP.
                       HT.    PL.HT  HT.            ueff     RECEPT  TYPE         FRAC.                                                                          GRAD.
                       (m)    (m)    (deg)  (m/s)   (m/s)     (m)                        (m/s)    (m/s)    (µg/m3)  (µg/m3)  (µg/m3)   (µg/m3)           (µg/m3)   (K/m)
--------------------------------------------------------------------------------------------------------------------------------------------------------------------------
P MERGE001       329   153.1  269.4  273.   2.669   9610.1   3242.0  GAU   0.025  0.000  0.200    0.052    35.017   0.000    0.000     0.000  PLUME OUT OF WAKE  0.01637
  MERGEN01      <--- Source is not emitting during this hour
P POINT002      1130    31.5  172.3  273.   1.347   4848.7 < 9157.9  GAU   0.090  0.000  0.200    0.074     2.209   2.209    2.422     0.066  PLUME OUT OF WAKE  0.01637
P POINT003       329    14.4  158.4  273.   1.347   4848.7   3202.3  GAU   0.073  0.000  0.200    0.074    13.187  13.019   14.021     0.330  1.000     13.187  0.01278
P POINT004      1099    30.6  172.3  273.   1.347   4848.7 < 8260.8  GAU   0.085  0.000  0.200    0.074     2.880   2.880    3.141     0.055  0.000      6.682  0.01278
P POINT005       325    16.2  158.4  273.   1.347   4848.7   2779.5  GAU   0.070  0.000  0.200    0.074    15.001  15.001   16.095     0.397  0.000     39.017  0.01278
P POINT006       332    14.6  158.4  273.   1.347   4848.7   3637.3  GAU   0.077  0.000  0.200    0.074    14.365  14.365   15.528     0.358  0.000     24.576  0.01278
P POINT007       333    15.6  158.4  273.   1.347   4848.7   3690.4  GAU   0.077  0.000  0.200    0.074    14.284  14.284   15.448     0.354  0.000     23.986  0.00781


VOLUME AND AREA SOURCES:
  SOURCE        RCPT   FINAL  DIST.  WDIR   Effect. <------ DISTANCE -----> MEAND. EFFECT.  EFFECT.  HOURLY   AERVAL     PANCAKE
  ID            NO.    PLUME  FINAL  FINAL  WSPD    3600*      TO    PLUME  FRAC.  SIGMA_V  SIGMA_W  CONC.    or
                       HT.    PL.HT  HT.            ueff     RECEPT  TYPE                                     VAL                  QTK      EMIFAC
                       (m)    (m)    (deg)  (m/s)   (m/s)     (m)                 (m/s)    (m/s)    (µg/m3)  (µg/m3)    (µg/m3)
--------------------------------------------------------------------------------------------------------------------------------------------------
  VOLUME01      <--- Source is not emitting during this hour
V VOLUME02      1105    45.0    0.0  273.   2.669   9610.1 <14473.7  DIR   0.083  0.200    0.052     0.002     0.002     0.000   N.A.     N.A.
  VOLUME03      <--- Source is not emitting during this hour
V VOLUME04      1105    45.0    0.0  273.   2.669   9610.1 <14255.1  DIR   0.082  0.200    0.052     0.002     0.002     0.000   N.A.     N.A.
  VOLUME05      <--- Source is not emitting during this hour
V VOLUME06       328     5.0    0.0  273.   0.929   3344.9   3055.8  DIR   0.222  0.200    0.079     0.507     0.648     0.017   N.A.     N.A.
  VOLUME07      <--- Source is not emitting during this hour
V VOLUME08      1090    35.0    0.0  273.   2.539   9141.4 <14347.0  DIR   0.114  0.200    0.054     0.025     0.029     0.001   N.A.     N.A.
  VOLUME09      <--- Source is not emitting during this hour
V VOLUME10       324     5.0    0.0  273.   0.929   3344.9   2681.8  DIR   0.217  0.200    0.079     0.634     0.804     0.021   N.A.     N.A.
A AREA01         325    10.0    0.0  273.   1.347   4848.7   3427.0  DIR   N.A.   0.200    0.074   236.915  0.237E+00     N.A.  0.1E-02  0.1E+07
```

DISTANCE-DEBUG assisted in the discovery of the AREACIRC issue associated with version16216

DISTANCE-DEBUG: Low-wind case

A case involving AERMOD 24-hour $PM_{2.5}$ modeling for the Class I PSD Increment SIL of 2 material handling transfer points at a concrete batch plant



Concrete Batch Plant Meterial Handling					
			Class I SIL		
Pollutant	Averaging Time	Year	Result (µg/m³)	SIL (µg/m³)	Pass or Fail
$PM_{2.5}$	24-hour	Year 1	0.25	0.27	Pass
		Year 2	0.29		Fail
		Year 3	0.24		Pass
		Year 4	0.18		Pass
		Year 5	0.16		Pass

DISTANCE-DEBUG: Low-wind Case

Point Sources	Q_s	H_s	T_s	V_s	D_s
	(g/s)	(m)	(K)	(m/s)	(m)
Turbine 1	1.0	30.0	810.0	37.0	4.5
Turbine 2	1.0	30.0	810.0	37.0	4.5

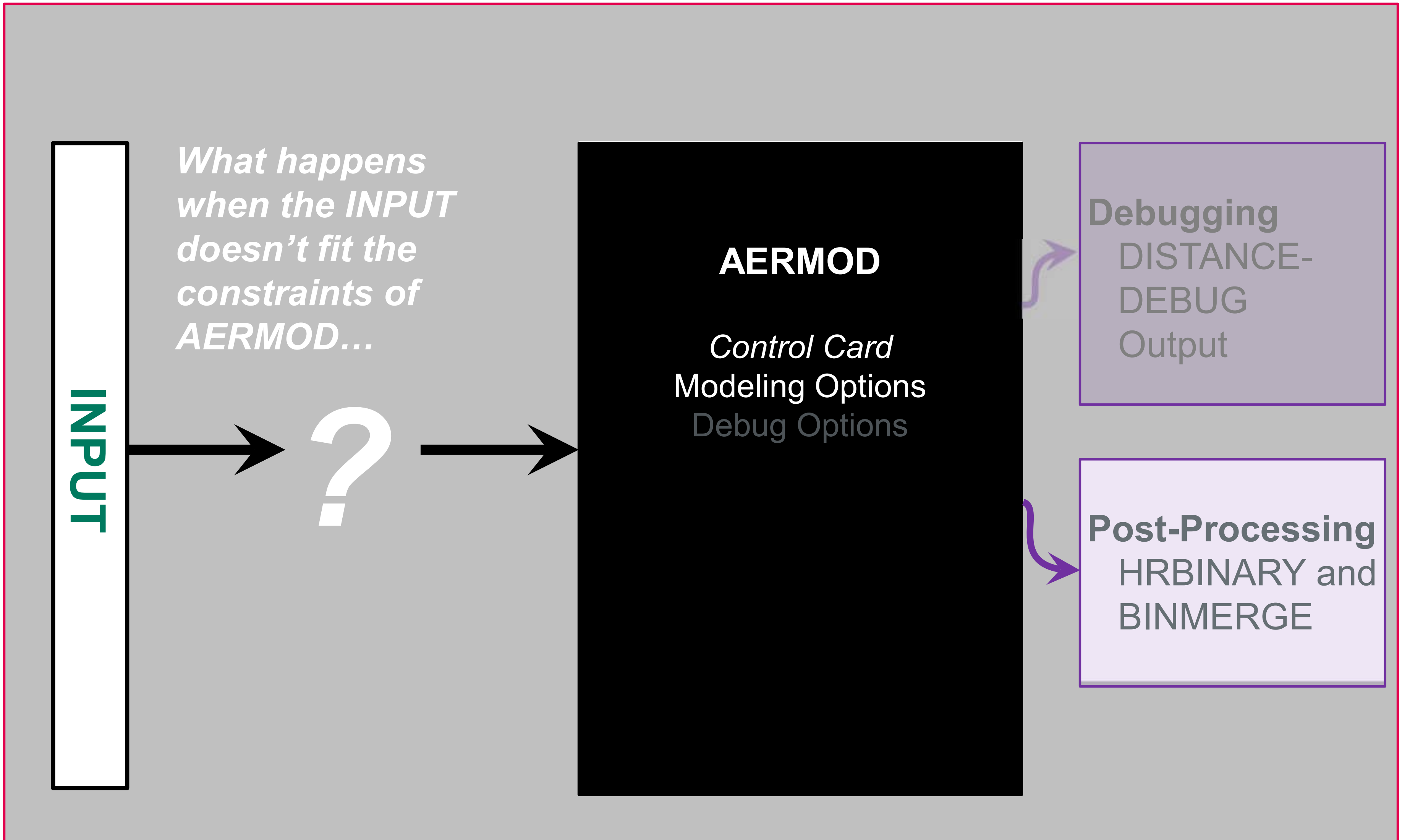
Volume Sources	Q_s	H_s	σ_y	σ_z
	(g/s)	(m)	(m)	(m)
Conveyor Loading	0.4	2	1.2	0.5
Conveyor Unloading	0.4	2	1.2	0.5

Hour	Source	u*	u_{eff}	1-hour Transit Distance	Conc
		(m/s)	(m/s)	(m)	μg/m^3
4	Turb1	0.04	1.4	4,888	0.001
	Turb2		1.4	4,888	0.001
	Load		0.5	1,795	0.591
	Unload		0.5	1,795	0.644
5	Turb1	0.02	0.7	2,412	0.001
	Turb2		0.7	2,412	0.001
	Load		0.5	1,767	1.426
	Unload		0.5	1,767	1.631
6	Turb1	0.07	0.8	2,924	0.062
	Turb2		0.8	2,924	0.062
	Load		0.7	2,634	1.692
	Unload		0.7	2,634	1.816

Case run using default meteorology

3 low wind speed hours result in questionably high impacts 50 km out (from two gravel drop points)

The AERMOD BlackBox



HRBINARY Post-processor

- "HRBINARY" allows for the import of an AERMOD unformatted 1-hour binary file to be added to any modeling run in order to perform the averaging of ranked highs for all currently evaluated averaging periods.

- Hence HRBINARY can allow output from multiple AERMOD runs of different sources to be merged, on an hour-by-hour, receptor-by-receptor basis

- When would this be necessary?

HRBINARY Example Case

- A steel mill with both stack and fugitive emission releases. Fugitive releases are represented by volume sources, area sources, and buoyant line sources (BLP). The BLP algorithms have been incorporated into AERMOD Version 16216r.
- The Plant operates 3 buoyant line sources.
- However, AERMOD v16216r allows only one set of average BLP parameters to be entered per run, these include the thermal buoyancy for line source and the associated downwash.

- Step 1:

  BINMERGE sums the separate AERMOD binary files for each different source groups. Each was modeled on the exact same grid.
- Step 2:

  AERMOD is re-run using the HRBINARY option. HRBINARY option takes the single merged binary file (from BINMERGE) and performs the pollutant and averaging time specific statistical ranking and averaging normally performed by AERMOD.

- Hence through this two-step method, very different sets of BLP source parameters can be more accurately represented in the modeling.

Further work

DISTANCE-DEBUG

- Does not currently support LINE, FLARE, BUOYLINE or OPENPIT sources
- Issue with reporting downwash contributions for impacts dominated by the “penetrated” plume type
- Provide an option for spreadsheet ready output

HRBINARY

- Allow for the acceptance of multiple binary files (thus eliminating the need for BINMERGE)
- For exploratory purposes, add an option to linearly scale concentrations in binary files for a weighted analysis between the binary files

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Attachment 3: HBP Code Modifications in AERMOD version 21112

Submitted to TCEQ: 4 August 2021

Appendix 3

HBP: Modifications to the AERMOD Code (Version 21112)

1.0 HBP: MODIFICATIONS TO THE AERMOD CODE

These are sections from the modified code. The line numbers reference their appearance in the modified version 21112 AERMOD. No changes have been made to the HBP code since, i.e. the code has not changed in the most recent version (23132) of AERMOD but the line numbers are different (due to changes elsewhere in the code).

The following modifications were written into the AERMOD code for implementing the HBP formulation. Lines numbers in the code are provided along with comments, some of which were added in the code itself.

Any code changes to correct for processing MAXDCONT output files are highlighted in yellow. Code changes associated with the added optional debug tool are highlighted in blue.

MODULES_HBP.FOR

MODULE MAIN1 in MODULES_HBP.FOR

After lines 243 added the FORTRAN unit number (HBPUNT) for the HBP Debug output file:

```
      INTEGER :: INUNIT, IOUNIT, MFUNIT, MPUNIT, IERUNT, IERWRT,
     &           IDPUNT, IDPUN2, IRSUNT, IEVUNT, ITEVUT, IHREMI,
     &           IBGUNT(6), IO3UNT(6), INCUNT, ISUMUNT, DBGUNT, DBMUNT,
     &           AREADBUNT, GDEPDBG, PDEPDBG, PRMDBUNT, PVMDBG, OLMDBG,
     &           ARM2DBG, RDISPUNT, AWMADWDBUNT, GRSMDBG, INOXUNT(6),
     &           TTRMUNT,
! Added for HBPDEBUG
     &           HBPUNT
! End add
```

After line 335, we added the logical switch DISTDBG for activating any loops involving the distance debug file:

```
      LOGICAL DFAULT, CONC, DEPOS, DDEP, WDEP, RURAL, URBAN, GRDRIS,
     &        NOSTD, NOBID, CLMPRO, MSGPRO, PERIOD, ANNUAL, MONTH,
     &        FLAT, ELEV, FLATSRCS, FLGPOL, RUN, EVENTS, RSTSAV,
     &        RSTINP, DAYTAB, MXFILE, PPFILE, PLFILE, ANPOST, ANPLOT,
     &        STATOK, MULTYR, TXFILE, RKFILE, SEASONHR,
     &        MXDAILY, MXDAILY_BYYR, L_MAXDCONT,
     &        DDPLETE, WDPLETE, DRYDPLT, WETDPLT, NODRYDPLT, NOWETDPLT,
     &        FSTCMP, EVONLY, SOCONT, DETAIL, NEWMET, ARDPLETE,
     &        PM25AVE, NO2AVE, SO2AVE, L_NO_PM25AVE, L_NO_NO2AVE,
     &        L_NO_SO2AVE, NOCHKD, NOWARN,
     &        DEBUG, METEORDBG, AREADBG, PRIMEDBG, PVMRMDBG, OLMDEBUG,
     &        ARM2DEBUG, GRSMDEBUG, DEPOSDBG, AWMADWDBG,
     &        L_WARNCHKD, SCIM, SCIMHR,
     &        FASTAREA, FASTALL, L_NonDFAULT,
     &        SCREEN, URBSTAB, PRM_FSTREC, ROMBERG,
     &        PVMRM, PSDCREDIT, OLM, L_MULTURB,
     &        L_PRESET_URBAN, L_UrbanTransition, L_URBAN_ALL,
     &        L_Urban, L_Rural,
     &        L_AWMADW,
     &        L_STRMLN_BLDG, L_RECT_BLDG, L_AWMA_Ueff, L_AWMA_UTurb,
     &        L_AWMA_ENTRAIN, L_ORDDW, L_AWMA_UTurbHX,
     &        L_ORD_Ueff, L_ORD_Turb, L_ORD_Cav,
     &        ARM2, BETA, L_ALPHA, L_PREINC, GRSM,
```

```
     &        RUNTTRM, TTRMDBG,
! Added for HBPDEBUG; August 2021
     &        HBPDBG
! End insert for HBPDEBUG
```

After line 385, we added the character variable DISFIL for saving the user input file name:

```
      CHARACTER (LEN=ILEN_FLD) :: SAVFIL, SAVFL2, INIFIL, EVFILE,
     &                            DBGFIL, DBMFIL, DBAREAFIL, DBPVFIL,
     &                                                       RDISPFIL,
     &                            DBOLMFIL, DBPRMFIL, DBAwmaDwFIL,
     &                            DBARM2FIL, DBGRSMFIL, OZONFL(6),
     &                            O3FILUNITS, O3VALUNITS, O3FORM(6),
     &                            OzoneUnits, URBNAM, NOXVALUNITS,
     &                            NOxUnits, NOXFL(6), NOXFILUNITS,
     &                            NOXFORM(6), TTRMFIL,
!    TTRMFIL is reserved for an unformatted POSTFILE for potential
!    post-processing using TTRM
!    end of TTRM insert
! Added for HBPDEBUG; August 2021
     &                            HBPFIL
! End HBPDEBUG insert
```

Lines 818:

```
C  ******************************** added code  --kja
C  ** variables for next hour convective and mechanical mixing heights
      DOUBLE PRECISION ::  ZICONVN, ZIMECHN
C  ******************************  added code end  --kja
! Added for MAXDCONT and EVENT processing; March 16, 2021
      DOUBLE PRECISION, ALLOCATABLE :: AZICONVN(:,:), AZIMECHN(:,:)
! End HIPMOD addition
```

Lines 1044:

```
C  ************************************  added code --kja
C  ** penetrated plume factor below mixing height - Weil's Fq term
      DOUBLE PRECISION ::  PPFN, ZIN, ZIAVG, HHTOP, HTOPDIF, HHBOT, PPWID
      DOUBLE PRECISION :: SZ3DBG
C  ***********************************  added code end  --kja
```

After line 1317, we assign the DISUNT unit number:

```
      DATA INUNIT/ 7/, IOUNIT/ 8/, PVMDBG/ 9/, OLMDBG/ 9/, ARMDBG/ 9/,
     &     IERUNT/10/, IERWRT/11/, IDPUNT/12/, IDPUN2/14/, IRSUNT/15/,
     &     IHREMI/16/, IEVUNT/17/, ITEVUT/18/, MFUNIT/19/, INCUNT/20/,
     &     MPUNIT/21/, ISUNIT/22/, IPUNIT/23/, DBGUNT/24/, DBMUNT/25/,
     &     AREADBUNT/26/, PRMDBUNT/27/, ISUMUNT/28/, GDEPDBG/29/,
     &     PDEPDBG/30/, DISUNT/31/, BINUNT/32/,
     &     RDISPUNT/ 3/,
     &     TTRMUNT/9937/,
! Added for HBPDEBUG; Aug. 2021
     &     HBPUNT/731/
! End insert for HBPDEBUG
```

SETUP_HBP.FOR

Added line 1250, which initializes the logical HBPDBG as “false.”

```
! Added for HBPDEBUG; Aug. 2021
      HBPDBG = .FALSE.
! End insert for HBPDBG
```

AERMOD_HBP.FOR

After line 808, added all the header information for the HBP debug file:

```
! Added for HBPDEBUG; August 2021
! added all the header information for the HBP debug file:

      IF(HBPDBG)THEN
C        Write the title(s) to the debug output file
         WRITE ( HBPUNT, 7601 )
         WRITE ( HBPUNT, 7100 ) TITLE1(1:68), TITLE2(1:68)
         WRITE ( HBPUNT,"(' ')")
         WRITE ( HBPUNT, 7701 )
 7100    FORMAT ( ' Title: ',A68,/,'        ',A68,/)
 7601    FORMAT (' * * * * * * * AERMOD HBP DEBUG FILE * * * * * * *')
 7701    FORMAT (' KURDAT,IREC,SCRID,Current_ZIC,Current_ZIM,',
     &           'NextHr_ZIC,NextHr_ZIM,Avg_ZI,Centerline_HE3,',
     &           'SigmaZ_SZ3,HTOP,HBOT,HTOPDIF,ZRT,PPF,PPFN,HBL_HRVAL')
!     &           'NO-HBL_HRVAL')
      ENDIF
! End HBRDEBUG insert
```

ALLRESULT Subroutine in AERMOD_HBP.FOR

Allocate arrays for next hour mixing heights for EVENT processing; lines 4687 – 4690:

```
! Added for HIPMOD; Aug. 2021
         ALLOCATE  (AZICONVN(NHR,1), AZIMECHN(NHR,1),
     &              STAT=IASTAT)
! End HIPMOD insert
```

Similarly, allocate arrays for next hour mixing heights for MAXDCONT processing; lines 5029 – 5032:

```
! Added for HIPMOD; Aug. 2021
         ALLOCATE  (AZICONVN(8784,NYEARS), AZIMECHN(8784,NYEARS),
     &              STAT=IASTAT)
! End HIPMOD insert
```

MAXD_METEXT Subroutine in AERMOD_HBP.FOR

Extract saved “next hour” mixing heights; lines 8039 – 8042:

```
! Added for HIPMOD; March 16, 2021
      ZICONVN = AZICONVN(IHR_NDX,IYR_NDX)
      ZIMECHN = AZIMECHN(IHR_NDX,IYR_NDX)
! End HIPMOD insert
```

CALC1_HBP.FOR

Write results to debug file at line 939; for hours not dominated by the penetrated plume (i.e. PPFN = 1), default values of -999.0 are written for most of the values:

```
! Added for HBPDEBUG; Aug. 2021
! Write out results to debug file
            IF(HBPDBG)THEN
              IF(PPFN .LT. 1)THEN
               WRITE(HBPUNT,7717) KURDAT,IREC,SRCID(isrc),ZICONV,ZIMECH,
     &                           ZICONVN,ZIMECHN,ZIAVG,HE3,SZ3DBG,HHTOP,
     &                           HHBOT,HTOPDIF,ZRT,PPF,PPFN,HRVAL!,
!     &                           NOHBP_HRVAL
              ELSE
               WRITE(HBPUNT,7817) KURDAT,IREC,SRCID(isrc),ZICONV,ZIMECH,
     &                           ZICONVN,ZIMECHN,ZRT,PPF,PPFN,HRVAL
              ENDIF
 7717       FORMAT(1x,I8.8,',',I6,',',A12,6(',',F8.2),',',F7.3,',',
     &             4(F8.2,','),F7.3,',',F7.3,',',F14.6)
 7817       FORMAT(1x,I8.8,',',I6,',',A12,4(',',F8.2),6(',-999.0'),',',
     &             F8.2,',',F7.3,',',F7.3,',',F14.6)
            ENDIF
! End HBPDEBUG insert
```

CPLUME Subroutine in CALC1_HBP.FOR

Modified conditional (lines 6309 – 6321, between asterisks):

```
            IF (PPF .LT. 1.0D0) THEN
C  ************************************* modified code  --kja
               COUT = (QTK * (1.0D0-PPF) / UEFFD) * ( FSUBYD*FSUBZD ) +
     &                (QTK * (1.0D0-PPF) / UEFFN) * ( FSUBYN*FSUBZN ) +
     &                (QTK * PPF*PPFN / UEFF3) * ( FSUBY3*FSUBZ3 )
C     &                (QTK * PPF / UEFF3) * ( FSUBY3*FSUBZ3 )

            ELSE
               COUT = (QTK * PPF*PPFN / UEFF3) * ( FSUBY3*FSUBZ3 )
C               COUT = (QTK * PPF / UEFF3) * ( FSUBY3*FSUBZ3 )
C  ************************************* modified code end  --kja

            END IF
```

COSET_HBP.FOR

Multiple additions in Subroutine DEBOUT (line 2919)

```
      SUBROUTINE DEBOPT
C*********************************************************************
C                 DEBOPT Module of AERMOD
C
```

```
C        PURPOSE: Process Debug Output File Option
C                 From Runstream Input Image
C
C        PROGRAMMER: Roger Brode
C
C        DATE:    September 30, 1993
C
C        MODIFIED    Modified to allow user to specify debug output
C                    for the GRSM NO2 option.
C                    CERC, 11/30/20
C
C        MODIFIED:   Modified to allow user to specify debug output
C                    for the PRIME downwash algorithm and for the
C                    OLM, ARM, or ARM2 options for modeling NO2.
C                    Portions of the MODEL debug outputs that were
C                    included in the main 'aermod.out' and in the
C                    'model.dbg' file will now be included in a
C                    separate PRIME debug file.
C                    R.W. Brode, U.S. EPA/OAQPS/AQMG, 01/29/2014
C
C        MODIFIED:   Modified to allow user to specify debug output
C                    only for PVMRM or deposition options on the
C                    DEBUGOPT keyword, avoiding large ouput files
C                    under the MODEL debug option. Debug output for
C                    PVMRM and/or deposition options will still be
C                    generated if the MODEL debug option is selected.
C                    See AERMOD User's Guide Addendum for details
C                    on the DEBUGOPT keyword.
C                    R.W. Brode, U.S. EPA/OAQPS/AQMG, 02/28/2011
C
C        INPUTS:  Input Runstream Image Parameters
C
C        OUTPUTS: Debug File Logical Switches and Filenames
C
C        ERROR HANDLING:   Checks for Too Few Parameters (uses default name);
C                          Checks for Too Many Parameters
C
C        CALLED FROM:   COCARD
C***********************************************************************
C
C     Variable Declarations
      USE MAIN1
      IMPLICIT NONE
      CHARACTER MODNAM*12, KOPT*8
      INTEGER :: I, IMOD, IMET, IAREA, IPRM, IPVM, IOLMD, IARM2, IDEP,
     &           IGRSM, NOPTS, MAXFields, IPRM2, ITTRMD,
! Added for HBPDEBUG; Aug. 2021
     &           IHBP
! End insert for HBPDEBUG

C     Variable Initializations
      MODNAM = 'DEBOPT'
C     Initialize counters for number of debug options and field number
C     associated with debugopts
      IMOD  = 0
      IMET  = 0
      IAREA = 0
      IPRM  = 0
      IPVM  = 0
      IOLMD = 0
      IARM2  = 0
      IDEP  = 0
```

```
      IGRSM = 0
      IPRM2 = 0
      NOPTS = 0
      MAXFields = 0
      ITTRMD = 0
      IHBP = 0

C     Check for Too Few or Too Many Parameters
      IF (IFC .LT. 3) THEN
C        WRITE Error Message     ! No Parameters
         CALL ERRHDL(PATH,MODNAM,'E','200',KEYWRD)
      ELSE IF (IFC .GT. 13) THEN
C        WRITE Warning Message   ! Too Many Parameters
         CALL ERRHDL(PATH,MODNAM,'E','202',KEYWRD)
      END IF

C --- First Check for Presence of Debug Switches;
C     also save position to interpret optional
C     filenames
      DO I = 3, IFC
         KOPT = FIELD(I)
         IF (KOPT .EQ. 'MODEL') THEN
            DEBUG = .TRUE.
            NOPTS = NOPTS + 1
            IMOD = I
         ELSE IF (KOPT .EQ. 'METEOR') THEN
            METEORDBG = .TRUE.
            NOPTS = NOPTS + 1
            IMET = I
         ELSE IF (KOPT .EQ. 'AREA') THEN
C ---       Check to see if AREADBG option has already been assigned .T.;
C           user may have entered both AREA and LINE
            IF (.NOT. AREADBG) THEN
C ---          AREADBG option not already = .T.; assign all variables
               AREADBG = .TRUE.
               NOPTS = NOPTS + 1
               IAREA = I
            ELSE
C ---          AREADBG already assigned = .T.; user may have entered
C              both AREA and LINE options; issue ERROR message
               CALL ERRHDL(PATH,MODNAM,'E','194','AREADEBUG')
               AREADBG = .FALSE.
            END IF
         ELSE IF (KOPT .EQ. 'LINE') THEN
C ---       Check to see if AREADBG option has already been assigned .T.;
C           user may have entered both AREA and LINE
            IF (.NOT. AREADBG) THEN
C ---          AREADBG option not already = .T.; assign all variables
               AREADBG = .TRUE.
               NOPTS = NOPTS + 1
               IAREA = I
            ELSE
C ---          AREADBG already assigned = .T.; user may have entered
C              both AREA and LINE options; issue ERROR message
               CALL ERRHDL(PATH,MODNAM,'E','194','LINEDEBUG')
               AREADBG = .FALSE.
            END IF
         ELSE IF (KOPT .EQ. 'PRIME') THEN
            PRIMEDBG = .TRUE.
            NOPTS = NOPTS + 1
            IPRM = I
         ELSE IF (KOPT .EQ. 'PVMRM') THEN
```

```
            PVMRMDBG = .TRUE.
            NOPTS = NOPTS + 1
            IPVM = I
         ELSE IF (KOPT .EQ. 'OLM') THEN
            OLMDEBUG = .TRUE.
            NOPTS = NOPTS + 1
            IOLMD = I
         ELSE IF (KOPT .EQ. 'ARM2') THEN
            ARM2DEBUG = .TRUE.
            NOPTS = NOPTS + 1
            IARM2 = I
         ELSE IF (KOPT .EQ. 'GRSM') THEN
            GRSMDEBUG = .TRUE.
            NOPTS = NOPTS + 1
            IGRSM = I
         ELSE IF (KOPT .EQ. 'DEPOS') THEN
            DEPOSDBG = .TRUE.
            NOPTS = NOPTS + 1
            IDEP = I
         ELSE IF (KOPT .EQ. 'AWMADW') THEN
            AWMADWDBG   = .TRUE.
            NOPTS = NOPTS + 1
            IPRM2 = I
          ELSE IF (KOPT .EQ. 'TTRM') THEN
            TTRMDBG = .TRUE.
            NOPTS = NOPTS + 1
            ITTRMD = I
          ELSE IF (KOPT .EQ. 'HBPDBG') THEN
            HBPDBG = .TRUE.
            NOPTS = NOPTS + 1
            IHBP = I
         END IF
      END DO

C --- Determine maximum number of fields allowed based on number of
C     options specified, assuming that user has specified filename
C     for each option (except for DEPOS).
      IF (NOPTS .GT. 0) THEN
         IF (.NOT.DEPOSDBG) THEN
            MAXFields = 2 + NOPTS*2
         ELSE
            MAXFields = 2 + (NOPTS-1)*2 + 1
         END IF
      ELSE
C        No recognizable debug options specified, issue fatal error
         WRITE(DUMMY,'(A:)') FIELD(3)(1:MIN(12,LEN_TRIM(FIELD(3))))
         CALL ERRHDL(PATH,MODNAM,'E','203',DUMMY)
         GO TO 999
      END IF

C --- Check for debug options without associated model option being used
      IF (PVMRMDBG .AND. .NOT. PVMRM) THEN
C        Write Error Message:  PVMRM debug without PVMRM option
         CALL ERRHDL(PATH,MODNAM,'E','194','PVMRMDBG')
      END IF
      IF (OLMDEBUG .AND. .NOT.OLM) THEN
C        Write Error Message:  OLM debug without OLM option
         CALL ERRHDL(PATH,MODNAM,'E','194','OLMDEBUG')
      END IF
      IF (ARM2DEBUG .AND. .NOT.ARM2) THEN
C        Write Error Message:  ARM2 debug without ARM2 option
         CALL ERRHDL(PATH,MODNAM,'E','194','ARM2DEBUG')
```

```
      END IF
      IF (GRSMDEBUG .AND. .NOT.GRSM) THEN
C        Write Error Message:  GRSM debug without GRSM option
         CALL ERRHDL(PATH,MODNAM,'E','194','GRSMDEBUG')
      END IF
      IF (TTRMDBG .AND. .NOT. RUNTTRM) THEN
C        Write Error Message:  TTRM debug without TTRM option
         CALL ERRHDL(PATH,MODNAM,'E','194','TTRMDEBUG')
      END IF
      IF (DEPOSDBG .AND. .NOT.DEPOS .AND. .NOT.DDEP .AND.
     &                                         .NOT.WDEP) THEN
C        Write Error Message:  DEPOS debug without deposition options
         CALL ERRHDL(PATH,MODNAM,'E','194','DEPOSDBG')
      END IF
      IF (AREADBG .AND. NAREA.EQ.0 .AND. NCIRC.EQ.0 .AND. NLINE.EQ.0
     &            .AND. NPIT.EQ.0) THEN
C        Write Error Message:  AREA/LINE debug without any applicable
C        sources
         IF (FIELD(IAREA) .EQ. 'AREA') THEN
            CALL ERRHDL(PATH,MODNAM,'E','194','AREADEBUG')
         ELSE IF (FIELD(IAREA) .EQ. 'LINE') THEN
            CALL ERRHDL(PATH,MODNAM,'E','194','LINEDEBUG')
         END IF
      END IF
      IF (PRIMEDBG .AND. NSEC.EQ.0) THEN
C        Write Error Message:  PRIME debug without any applicable sources
         CALL ERRHDL(PATH,MODNAM,'E','194','PRIMEDBG')
      END IF

      IF (AWMADWDBG .AND. NSEC.EQ.0) THEN
C        Write Error Message:  AWMADW debug without any applicable sources
         CALL ERRHDL(PATH,MODNAM,'E','194','AWMADWDBG')
      END IF

C --- Check for user-specified filenames, which should immediately
C     follow the keyword option in the input file
      IF (DEBUG) THEN
         IF (IFC .GE. IMOD+1 .AND.
     &        FIELD(IMOD+1) .NE. 'METEOR' .AND.
     &        FIELD(IMOD+1) .NE. 'AREA' .AND.
     &        FIELD(IMOD+1) .NE. 'LINE' .AND.
     &        FIELD(IMOD+1) .NE. 'PRIME' .AND.
     &        FIELD(IMOD+1) .NE. 'PVMRM' .AND.
     &        FIELD(IMOD+1) .NE. 'OLM' .AND.
     &        FIELD(IMOD+1) .NE. 'ARM2' .AND.
     &        FIELD(IMOD+1) .NE. 'GRSM' .AND.
     &        FIELD(IMOD+1) .NE. 'DEPOS'.AND.
     &        FIELD(IMOD+1) .NE. 'AWMADW' .AND.
     &        FIELD(IMOD+1) .NE. 'HBPDBG' .AND.
     &        FIELD(IMOD+1) .NE. 'TTRM') THEN

C ---       Assign user-specified filename for the MODEL debug option
            DBGFIL = RUNST1(LOCB(IMOD+1):LOCE(IMOD+1))
         ELSE
C ---       Assign default MODEL debug filename
            DBGFIL = 'MODEL.DBG'
         END IF
      END IF

      IF (METEORDBG) THEN
         IF (IFC .GE. IMET+1 .AND.
     &        FIELD(IMET+1) .NE. 'MODEL' .AND.
```

```
     &       FIELD(IMET+1) .NE. 'AREA' .AND.
     &       FIELD(IMET+1) .NE. 'LINE' .AND.
     &       FIELD(IMET+1) .NE. 'PRIME' .AND.
     &       FIELD(IMET+1) .NE. 'PVMRM' .AND.
     &       FIELD(IMET+1) .NE. 'OLM' .AND.
     &       FIELD(IMET+1) .NE. 'ARM2' .AND.
     &       FIELD(IMET+1) .NE. 'GRSM' .AND.
     &       FIELD(IMET+1) .NE. 'DEPOS' .AND.
     &       FIELD(IMET+1) .NE. 'AWMADW' .AND.
     &       FIELD(IMET+1) .NE. 'HBPDBG' .AND.
     &       FIELD(IMET+1) .NE. 'TTRM') THEN

C ---       Assign user-specified filename for the METEOR debug option
            DBMFIL = RUNST1(LOCB(IMET+1):LOCE(IMET+1))
         ELSE
C ---       Assign default METEOR debug filename
            DBMFIL = 'METEOR.DBG'
         END IF
      END IF

      IF (AREADBG) THEN
         IF (IFC .GE. IAREA+1 .AND.
     &       FIELD(IAREA+1) .NE. 'MODEL' .AND.
     &       FIELD(IAREA+1) .NE. 'METEOR' .AND.
     &       FIELD(IAREA+1) .NE. 'PRIME' .AND.
     &       FIELD(IAREA+1) .NE. 'PVMRM' .AND.
     &       FIELD(IAREA+1) .NE. 'OLM' .AND.
     &       FIELD(IAREA+1) .NE. 'ARM2' .AND.
     &       FIELD(IAREA+1) .NE. 'GRSM' .AND.
     &       FIELD(IAREA+1) .NE. 'DEPOS' .AND.
     &       FIELD(IAREA+1) .NE. 'AWMADW' .AND.
     &       FIELD(IAREA+1) .NE. 'HBPDBG' .AND.
     &       FIELD(IAREA+1) .NE. 'TTRM') THEN

C ---       Assign user-specified filename for the AREA debug option
            DBAREAFIL = RUNST1(LOCB(IAREA+1):LOCE(IAREA+1))
         ELSE
C ---       Assign default AREA debug filename
            DBAREAFIL = 'AREA.DBG'
         END IF
      END IF

      IF (PRIMEDBG) THEN
         IF (IFC .GE. IPRM+1 .AND.
     &       FIELD(IPRM+1) .NE. 'MODEL' .AND.
     &       FIELD(IPRM+1) .NE. 'METEOR' .AND.
     &       FIELD(IPRM+1) .NE. 'AREA' .AND.
     &       FIELD(IPRM+1) .NE. 'LINE' .AND.
     &       FIELD(IPRM+1) .NE. 'PVMRM' .AND.
     &       FIELD(IPRM+1) .NE. 'OLM' .AND.
     &       FIELD(IPRM+1) .NE. 'ARM2' .AND.
     &       FIELD(IPRM+1) .NE. 'GRSM' .AND.
     &       FIELD(IPRM+1) .NE. 'DEPOS' .AND.
     &       FIELD(IPRM+1) .NE. 'AWMADW' .AND.
     &       FIELD(IPRM+1) .NE. 'HBPDBG' .AND.
     &       FIELD(IPRM+1) .NE. 'TTRM') THEN

C ---       Assign user-specified filename for the PRIME debug option
            DBPRMFIL = RUNST1(LOCB(IPRM+1):LOCE(IPRM+1))
         ELSE
C ---       Assign default PRIME debug filename
            DBPRMFIL = 'PRIME.DBG'
```

```
            END IF
         END IF

         IF (PVMRMDBG) THEN
            IF (IFC .GE. IPVM+1 .AND.
     &          FIELD(IPVM+1) .NE. 'MODEL' .AND.
     &          FIELD(IPVM+1) .NE. 'METEOR' .AND.
     &          FIELD(IPVM+1) .NE. 'AREA' .AND.
     &          FIELD(IPVM+1) .NE. 'LINE' .AND.
     &          FIELD(IPVM+1) .NE. 'PRIME' .AND.
     &          FIELD(IPVM+1) .NE. 'OLM' .AND.
     &          FIELD(IPVM+1) .NE. 'ARM2' .AND.
     &          FIELD(IPVM+1) .NE. 'GRSM' .AND.
     &          FIELD(IPVM+1) .NE. 'DEPOS' .AND.
     &          FIELD(IPVM+1) .NE. 'AWMADW' .AND.
     &          FIELD(IPVM+1) .NE. 'HBPDBG' .AND.
     &          FIELD(IPVM+1) .NE. 'TTRM') THEN

C ---          Assign user-specified filename for the PVMRM debug option
               DBPVFIL = RUNST1(LOCB(IPVM+1):LOCE(IPVM+1))
            ELSE
C ---          Assign default PVMRM debug filename
               IF (PVMRM) THEN
                  DBPVFIL = 'PVMRM.DBG'
               END IF
            END IF
C ---       Assign default filename for RELDISP debug file for PVMRM option
            RDISPFIL = 'RelDisp.dbg'
         END IF

         IF (OLMDEBUG) THEN
            IF (IFC .GE. IOLMD+1 .AND.
     &          FIELD(IOLMD+1) .NE. 'MODEL' .AND.
     &          FIELD(IOLMD+1) .NE. 'METEOR' .AND.
     &          FIELD(IOLMD+1) .NE. 'AREA' .AND.
     &          FIELD(IOLMD+1) .NE. 'LINE' .AND.
     &          FIELD(IOLMD+1) .NE. 'PRIME' .AND.
     &          FIELD(IOLMD+1) .NE. 'PVMRM' .AND.
     &          FIELD(IOLMD+1) .NE. 'ARM2' .AND.
     &          FIELD(IOLMD+1) .NE. 'GRSM' .AND.
     &          FIELD(IOLMD+1) .NE. 'DEPOS' .AND.
     &          FIELD(IOLMD+1) .NE. 'AWMADW' .AND.
     &          FIELD(IOLMD+1) .NE. 'HBPDBG' .AND.
     &          FIELD(IOLMD+1) .NE. 'TTRM') THEN

C ---          Assign user-specified filename for the OLM debug option
               DBOLMFIL = RUNST1(LOCB(IOLMD+1):LOCE(IOLMD+1))
            ELSE
C ---          Assign default OLM debug filename
               DBOLMFIL = 'OLM.DBG'
            END IF
         END IF

         IF (ARM2DEBUG) THEN
            IF (IFC .GE. IARM2+1 .AND.
     &          FIELD(IARM2+1) .NE. 'MODEL' .AND.
     &          FIELD(IARM2+1) .NE. 'METEOR' .AND.
     &          FIELD(IARM2+1) .NE. 'AREA' .AND.
     &          FIELD(IARM2+1) .NE. 'LINE' .AND.
     &          FIELD(IARM2+1) .NE. 'PRIME' .AND.
     &          FIELD(IARM2+1) .NE. 'PVMRM' .AND.
     &          FIELD(IARM2+1) .NE. 'OLM' .AND.
```

```
     &        FIELD(IARM2+1) .NE. 'GRSM' .AND.
     &        FIELD(IARM2+1) .NE. 'DEPOS' .AND.
     &        FIELD(IARM2+1) .NE. 'AWMADW' .AND.
     &        FIELD(IARM2+1) .NE. 'HBPDBG' .AND.
     &        FIELD(IARM2+1) .NE. 'TTRM') THEN

C ---       Assign user-specified filename for the ARM2 debug option
            DBARM2FIL = RUNST1(LOCB(IARM2+1):LOCE(IARM2+1))
         ELSE
C ---       Assign default ARM2 debug filename
            DBARM2FIL = 'ARM2.DBG'
         END IF
      END IF

C     CERC 11/30/20 Code for determining GRSM debug file name
      IF (GRSMDEBUG) THEN
         IF (IFC .GE. IGRSM+1 .AND.
     &        FIELD(IGRSM+1) .NE. 'MODEL' .AND.
     &        FIELD(IGRSM+1) .NE. 'METEOR' .AND.
     &        FIELD(IGRSM+1) .NE. 'AREA' .AND.
     &        FIELD(IGRSM+1) .NE. 'LINE' .AND.
     &        FIELD(IGRSM+1) .NE. 'PRIME' .AND.
     &        FIELD(IGRSM+1) .NE. 'OLM' .AND.
     &        FIELD(IGRSM+1) .NE. 'PVMRM' .AND.
     &        FIELD(IGRSM+1) .NE. 'ARM2' .AND.
     &        FIELD(IGRSM+1) .NE. 'DEPOS' .AND.
     &        FIELD(IGRSM+1) .NE. 'AWMADW' .AND.
     &        FIELD(IGRSM+1) .NE. 'HBPDBG' .AND.
     &        FIELD(IGRSM+1) .NE. 'TTRM') THEN
C ---       Assign user-specified filename for the GRSM debug option
            DBGRSMFIL = RUNST1(LOCB(IGRSM+1):LOCE(IGRSM+1))
         ELSE
C ---       Assign default GRSM debug filename
            DBGRSMFIL = 'GRSM.DBG'
         END IF
      END IF

      IF (AWMADWDBG) THEN
         IF (IFC .GE. IPRM2+1 .AND.
     &        FIELD(IPRM2+1) .NE. 'MODEL' .AND.
     &        FIELD(IPRM2+1) .NE. 'METEOR' .AND.
     &        FIELD(IPRM2+1) .NE. 'AREA' .AND.
     &        FIELD(IPRM2+1) .NE. 'LINE' .AND.
     &        FIELD(IPRM2+1) .NE. 'PRIME' .AND.
     &        FIELD(IPRM2+1) .NE. 'PVMRM' .AND.
     &        FIELD(IPRM2+1) .NE. 'OLM' .AND.
     &        FIELD(IPRM2+1) .NE. 'ARM2' .AND.
     &        FIELD(IPRM2+1) .NE. 'GRSM' .AND.
     &        FIELD(IPRM2+1) .NE. 'TTRM' .AND.
     &        FIELD(IPRM2+1) .NE. 'HBPDBG' .AND.
     &        FIELD(IPRM2+1) .NE. 'DEPOS') THEN

C ---       Assign user-specified filename for the PRIME debug option
            DBAwmaDwFIL = RUNST1(LOCB(IPRM2+1):LOCE(IPRM2+1))
         ELSE
C ---       Assign default AWMADW debug filename
            DBAwmaDwFIL = 'AWMADW.DBG'
         END IF
      END IF

C --- Now check for DEPOS option; since DEPOS debug filenames are
C     hardwired, issue warning if user appears to have specified
```

```
C      a filename
       IF (DEPOSDBG) THEN
C          JAT 05/08/2020 added from version 19191
C          wet deposition parameters are written to debug file
c          regardless if MODEL debug is chosen.  if model debug
c          not chosen, file is fort.24.  change to DEPOS.DBG
c          if dbgfil not named or next field is not MODEL
          IF (TRIM(ADJUSTL(DBGFIL)) .EQ. '' .OR. FIELD(IDEP+1) .NE.
     &    'MODEL') DBGFIL='DEPOS.DBG'
          IF (IFC .GE. IDEP+1 .AND.
     &        FIELD(IDEP+1) .NE. 'MODEL' .AND.
     &        FIELD(IDEP+1) .NE. 'METEOR' .AND.
     &        FIELD(IDEP+1) .NE. 'AREA' .AND.
     &        FIELD(IDEP+1) .NE. 'LINE' .AND.
     &        FIELD(IDEP+1) .NE. 'PRIME' .AND.
     &        FIELD(IDEP+1) .NE. 'PVMRM' .AND.
     &        FIELD(IDEP+1) .NE. 'ARM2' .AND.
     &        FIELD(IDEP+1) .NE. 'OLM' .AND.
     &        FIELD(IDEP+1) .NE. 'GRSM' .AND.
     &        FIELD(IDEP+1) .NE. 'TTRM' .AND.
     &        FIELD(IDEP+1) .NE. 'HBPDBG' .AND.
     &        FIELD(IDEP+1) .NE. 'AWMADW') THEN

C ---        Write warning message regarding DEPOS debug filenames
             CALL ERRHDL(PATH,MODNAM,'W','203','DEPOSDBG')
          END IF
       END IF

!    Added for TTRM; AECOM
       IF (TTRMDBG) THEN
          IF (IFC .GE. ITTRMD+1 .AND.
     &        FIELD(ITTRMD+1) .NE. 'METEOR' .AND.
     &        FIELD(ITTRMD+1) .NE. 'MODEL' .AND.
     &        FIELD(ITTRMD+1) .NE. 'PRIME' .AND.
     &        FIELD(ITTRMD+1) .NE. 'PVMRM' .AND.
     &        FIELD(ITTRMD+1) .NE. 'OLM' .AND.
     &        FIELD(ITTRMD+1) .NE. 'ARM2' .AND.
     &        FIELD(ITTRMD+1) .NE. 'GRSM' .AND.
     &        FIELD(ITTRMD+1) .NE. 'AREA' .AND.
     &        FIELD(ITTRMD+1) .NE. 'LINE' .AND.
     &        FIELD(ITTRMD+1) .NE. 'AWMADW' .AND.
     &        FIELD(ITTRMD+1) .NE. 'HBPDBG' .AND.
     &        FIELD(ITTRMD+1) .NE. 'DEPOS') THEN
!      added for TTRM; AECOM
C ---        Assign user-specified filename for the TTRM debug option
             TTRMFIL = RUNST1(LOCB(ITTRMD+1):LOCE(ITTRMD+1))
          ELSE
C ---        Assign default Ozone Reaction Rate debug filename
             TTRMFIL = 'TTRM_DEBUG.DBG'
          END IF
       END IF
!    End TTRM insert; Feb. 2021

!    Added for HBP; Aug. 2021
       IF (HBPDBG) THEN
          IF (IFC .GE. IHBP+1 .AND.
     &        FIELD(IHBP+1) .NE. 'METEOR' .AND.
     &        FIELD(IHBP+1) .NE. 'MODEL' .AND.
     &        FIELD(IHBP+1) .NE. 'PRIME' .AND.
     &        FIELD(IHBP+1) .NE. 'PVMRM' .AND.
     &        FIELD(IHBP+1) .NE. 'OLM' .AND.
     &        FIELD(IHBP+1) .NE. 'ARM2' .AND.
```

```
     &       FIELD(IHBP+1) .NE. 'GRSM' .AND.
     &       FIELD(IHBP+1) .NE. 'AREA' .AND.
     &       FIELD(IHBP+1) .NE. 'LINE' .AND.
     &       FIELD(IHBP+1) .NE. 'AWMADW' .AND.
     &       FIELD(IHBP+1) .NE. 'HBPDBG' .AND.
     &       FIELD(IHBP+1) .NE. 'DEPOS') THEN
!     added for HBP; AECOM
C ---       Assign user-specified filename for the HBP debug option
            HBPFIL = RUNST1(LOCB(IHBP+1):LOCE(IHBP+1))
         ELSE
C ---       Assign default HBP debug filename
            HBPFIL = 'HBP_DEBUG.DBG'
         END IF
      END IF
!   End HBPDEBUG insert

C --- Open MODEL, METEOR, AREA, PRIME and AWMADW debug files, if selected;
C     note that PVMRM, OLM, ARM2, GRSM and DEPOS debug files are opened
C     elsewhere
C Unused:  200 FORMAT ( ' OPTIONS: ', A /)
c     JAT 05/08/2020 ADD CODE TO OPEN IF DEBUG OR DEPOSDBG
C     BECAUSE IT USES THE DEBUGFIL AS WELL
C      IF (DEBUG) THEN
      IF (DEBUG .OR. DEPOSDBG) THEN
C        Open debug output file
         DUMMY = 'DebugFile'
         OPEN (UNIT=DBGUNT,FILE=DBGFIL,ERR=91,STATUS='REPLACE')
      END IF

      GOTO 101

C     WRITE Error Message:  Error Opening File
 91   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 101  CONTINUE

      IF (METEORDBG) THEN
C        Open debug meteorology output file
         DUMMY = 'DbgMetFile'
         OPEN (UNIT=DBMUNT,FILE=DBMFIL,ERR=92,STATUS='REPLACE')
      END IF

      GOTO 102

C     WRITE Error Message:  Error Opening File
 92   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 102  CONTINUE

      IF (AREADBG) THEN
C        Open debug AREA output file
         DUMMY = 'AreaDbgFile'
         OPEN (UNIT=AREADBUNT,FILE=DBAREAFIL,ERR=93,STATUS='REPLACE')
      END IF

      GOTO 103

C     WRITE Error Message:  Error Opening File
 93   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 103  CONTINUE
```

```
      IF (PRIMEDBG) THEN
C        Open debug PRIME output file
         DUMMY = 'PrimeDbgFile'
         OPEN (UNIT=PRMDBUNT,FILE=DBPRMFIL,ERR=94,STATUS='REPLACE')
      END IF

      GOTO 104

C     WRITE Error Message:  Error Opening File
 94   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 104  CONTINUE

      IF (AWMADWDBG) THEN
C        Open debug AWMADW output file
         DUMMY = 'AwmaDwDbgFile'
         OPEN (UNIT=AwmaDwDBUNT,FILE=DBAwmaDwFIL,ERR=95,
     &         STATUS='REPLACE')
      END IF

      GOTO 105

C     WRITE Error Message:  Error Opening File
 95   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 105  CONTINUE


      IF (TTRMDBG) THEN
!        Open TTRM output file
         DUMMY = 'TTRMFIL'
         OPEN (UNIT=TTRMUNT,FILE=TTRMFIL,ERR=96,STATUS='REPLACE')
         WRITE(TTRMUNT,'(''TTRM Debug File'',51x,a8,/70x,a8)')
     &                                           rundat, runtim
      END IF

      GOTO 106

C     WRITE Error Message:  Error Opening File
 96   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 106  CONTINUE

      IF (HBPDBG) THEN
!        Open TTRM output file
         DUMMY = 'HBPFIL'
         OPEN (UNIT=HBPUNT,FILE=HBPFIL,ERR=797,STATUS='REPLACE')
         WRITE(HBPUNT,'(''HBP Debug File'',51x,a8,/70x,a8)')
     &                                           rundat, runtim
      END IF

      GOTO 7107

C     WRITE Error Message:  Error Opening File
 797  CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 7107 CONTINUE


CCRT 3/22/2021: File is checked and opened in aermod.f
CCRT comment out this code - leave for reference if needed later
CCRT      IF (GRSMDEBUG) THEN
```

```
CCRT!        Open GRSM output file
CCRT         DUMMY = 'GRSMFIL'
CCRT         OPEN (UNIT=GRSMDBG,FILE=DBGRSMFIL,ERR=97,STATUS='REPLACE')
CCRT         WRITE(GRSMDBG,'(''GRSM Debug File'',51x,a8,/70x,a8)')
CCRT     &                                           rundat, runtim
CCRT      END IF
CCRT
CCRT      GOTO 107
CCRT
CCRTC     WRITE Error Message:  Error Opening File
CCRT 97   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 107  CONTINUE



      IF (IFC .GT. MAXFields) THEN
C        Maximum number of fields exceeded, issue warning message,
C        including up to 12 characters from last field
         WRITE(DUMMY,'(A:)') FIELD(IFC)(1:MIN(12,LEN_TRIM(FIELD(IFC))))
         CALL ERRHDL(PATH,MODNAM,'E','203',DUMMY)
      END IF

      GO TO 999

C     WRITE Error Message:  Error Opening File
C Unused:  99   CALL ERRHDL(PATH,MODNAM,'E','500',DUMMY)

 999  RETURN
      END

!*********************************************************************************
```

METEXT_HBP.FOR

METEXT Subroutine in METEXT_HBP.FOR

Added code for extracting the mixing height for the next hour between lines 479 – 512:

```
C  **************************************** added code --kja
C ** Get next hours mixing heights in needed
C ** Read next hour to get next mixing height for unstable conditions
         IF (OBULEN .LT. 0.0D0 .AND. OBULEN .GT. -9.9D4) THEN
          READ( MFUNIT, *, END=1006, ERR=99, IOSTAT=IOERRN ) IYEAR,
     &          IMONTH, IDAY, IJDAY, IHOUR, SFCHF, USTAR, WSTAR,
     &          VPTGZI, ZICONVN, ZIMECHN, OBULEN, SFCZ0, BOWEN, ALBEDO,
     &          UREF, WDREF, UREFHT, TA, TREFHT, IPCODE, PRATE, RH,
     &          SFCP, NCLOUD
C ** Check for missing next hour IE. OBULEN =-99999.0
          IF(OBULEN .LT. -9.9D4) GOTO 1006
          BACKSPACE MFUNIT
          BACKSPACE MFUNIT
          READ( MFUNIT, *, END=1000, ERR=99, IOSTAT=IOERRN ) IYEAR,
     &          IMONTH, IDAY, IJDAY, IHOUR, SFCHF, USTAR, WSTAR,
     &          VPTGZI, ZICONV, ZIMECH, OBULEN, SFCZ0, BOWEN, ALBEDO,
     &          UREF, WDREF, UREFHT, TA, TREFHT, IPCODE, PRATE, RH,
```

```
     &         SFCP, NCLOUD
          GOTO 1003
1006      ZICONVN = -999.0D0
          ZIMECHN = -999.0D0
          BACKSPACE MFUNIT
          BACKSPACE MFUNIT
          READ( MFUNIT, *, END=1000, ERR=99, IOSTAT=IOERRN ) IYEAR,
     &         IMONTH, IDAY, IJDAY, IHOUR, SFCHF, USTAR, WSTAR,
     &         VPTGZI, ZICONV, ZIMECH, OBULEN, SFCZ0, BOWEN, ALBEDO,
     &         UREF, WDREF, UREFHT, TA, TREFHT, IPCODE, PRATE, RH,
     &         SFCP, NCLOUD
1003      CONTINUE
         ELSE
           ZICONVN = -999.0D0
           ZIMECHN = -999.0D0
         END IF
C  **************************************  added code end --kja
```

For MAXDCONT processing, save the next hour's mixing heights; lines 816 – 819:

```
! Added for HIPMOD; Aug. 2021
            AZICONVN(IHR_NDX,IYR_NDX) = ZICONVN
            AZIMECHN(IHR_NDX,IYR_NDX) = ZIMECHN
! End HIPMOD Insert
```

IBVAL_HBP.FOR

*Highlighted comments correspond to example cases in the spreadsheet "*Spreadsheet_calculation_for_PPFN_examples-v5.xlsx"

IBVAL (XARG) Subroutine in IBVAL_HBP.FOR

Lines 70 - 75: Initialize the value of PPFN; it will be later recalculated based on the location of the penetrated plume in relation to the mixing height (Lines 319 – 350).

```
C  *********************************added code --kja
C  **  PPFN should be 1 when mixing height > top of penetrated plume
      IF (HBPLUME) THEN
         PPFN = 1.0D0
      ENDIF
C  *********************************added code end --kja
```

Lines 159 – 177: Shows the calculation of the average mixing height based on the current and next hours' mixing heights.

```
C  ******************************* added code --kja
C ** determine next hour mix height ZIN from mechanical and convective heights
           IF(ZICONVN .GT. 0.0D0 .AND. ZIMECHN .GT. 0.0D00) THEN
             ZIN = MAX(ZICONVN,ZIMECHN)
           ELSEIF( ZICONVN .LT. 0.0D0 .AND. ZIMECHN .GT. 0.0D0) THEN
             ZIN = ZIMECHN
           ELSEIF( ZICONVN .GT. 0.0D0 .AND. ZIMECHN .LT. 0.0D0) THEN
             ZIN = ZICONVN
           ELSE
```

```
            ZIN = ZI
          END IF
C ** Calculate average height between hours
          ZIAVG = (ZI+ZIN)/2.0D0
          IF(DEBUG) THEN
           WRITE(DBGUNT,6019) ZICONVN, ZIMECHN, ZIN,ZIAVG, HE3
6019       FORMAT(1X,'CONVN= ',F10.2,' MECHN= ',F10.2,' ZIN= ',F10.2,
     &      'ZIAVG= ',F10.2,'HE3= ',F10.2)
          END IF
C  ******************************* added code end --kja
```

Lines 319 – 350: Conditional block for assessing varying cases for calculating the weighting factor PPFN.

```
C  **************************************************  added code --kja
C  ** how much of penetrated plume still above ZIAVG
C  ** assuming gaussian entrainment factor
            HHTOP = HE3 + 2.15D0*SZ3  ! top of plume
            HHBOT = MAX(HE3 - 2.15D0*SZ3,ZRT)  ! Bottom of plume
C ** width of plume to 2.15 sigma-z - where conc. falls to 10% of centerline
            PPWID = HHTOP - HHBOT
C ** difference between top of plume and ZIAVG mixing height
            HTOPDIF = HHTOP - ZIAVG
            IF (HTOPDIF .GT. 0.0D0) THEN  ! top of plume > mixing ht
C ** PPFN should be between 0 - 1
              IF(HTOPDIF .LT. PPWID) THEN ! mixing ht within plume
                IF(ZIAVG .LE. HE3) THEN
C ** PPFN from 0 to 0.5 - amount of penetrated plume entrained
C ** lower half of plume
```

Case 3a: Partial contribution of the penetrated plume to the ground-level concentration ZIAVG is between HHBOT and HE3, so PPFN should be less than 0.5.

```
                 PPFN = 0.5D0*ERF((ZIAVG-HHBOT)/SZ3/DSQRT(2.0D0))
                ELSE
C ** PPFN from 0.5 to 1.0 - amount of penetrated plume entrained
C ** more than half of plume entrained
```

Case 3b: Partial contribution of the penetrated plume to the ground-level concentration ZIAVG is between HE3 and HHTOP, so PPFN should be greater than 0.5.

```
                 PPFN = 0.5D0*(1.0D0 +
     &                  ERF((ZIAVG-HE3)/SZ3/DSQRT(2.0D0)))
                ENDIF
              ELSE
C ** whole penetrated plume is still above average mixing height
C ** no contribution from penetrated plume
```

Case 1: No contribution of the penetrated plume to the ground-level concentration

```
                PPFN = 0.0D0
              ENDIF
            ELSE
C ** whole penetrated plume below ZIAVG
```

Case 2: ALL of the penetrated plume is available to contribute to the ground-level concentration.

```
              PPFN = 1.0D0
            END IF
            SZ3DBG = SZ3
C  **************************************************  added code end --kja
```

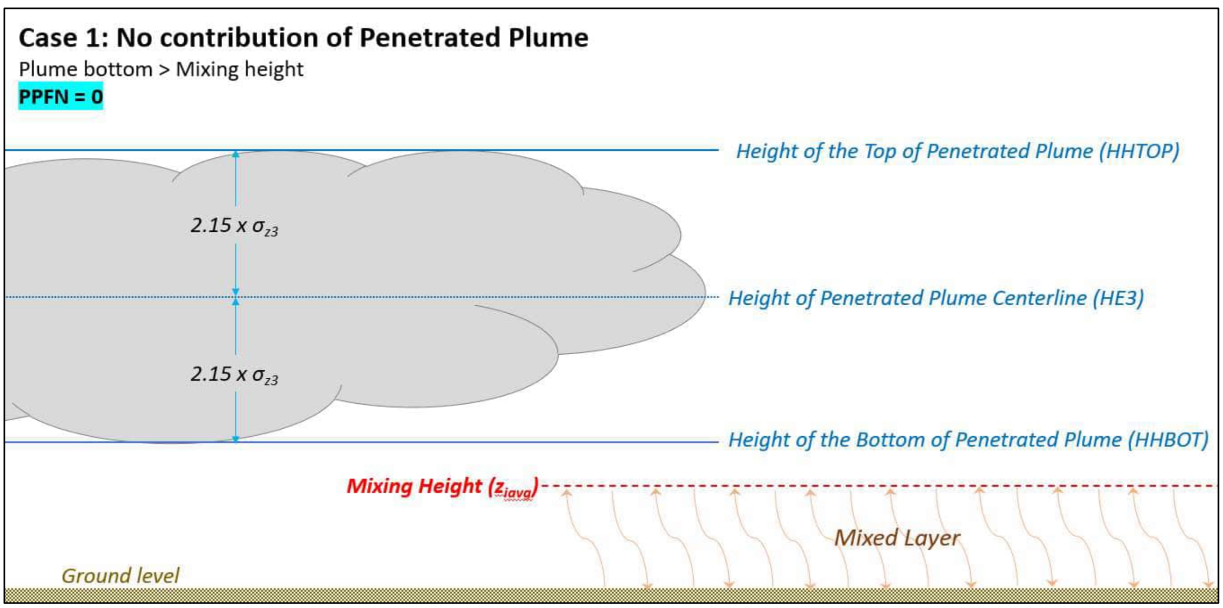
Attachment 4: Example Calculations for PPFN

Spreadsheet illustrating the implementation of the HBP formulation (input variables are highlighted in yellow)
Calculations are highlighted in orange.

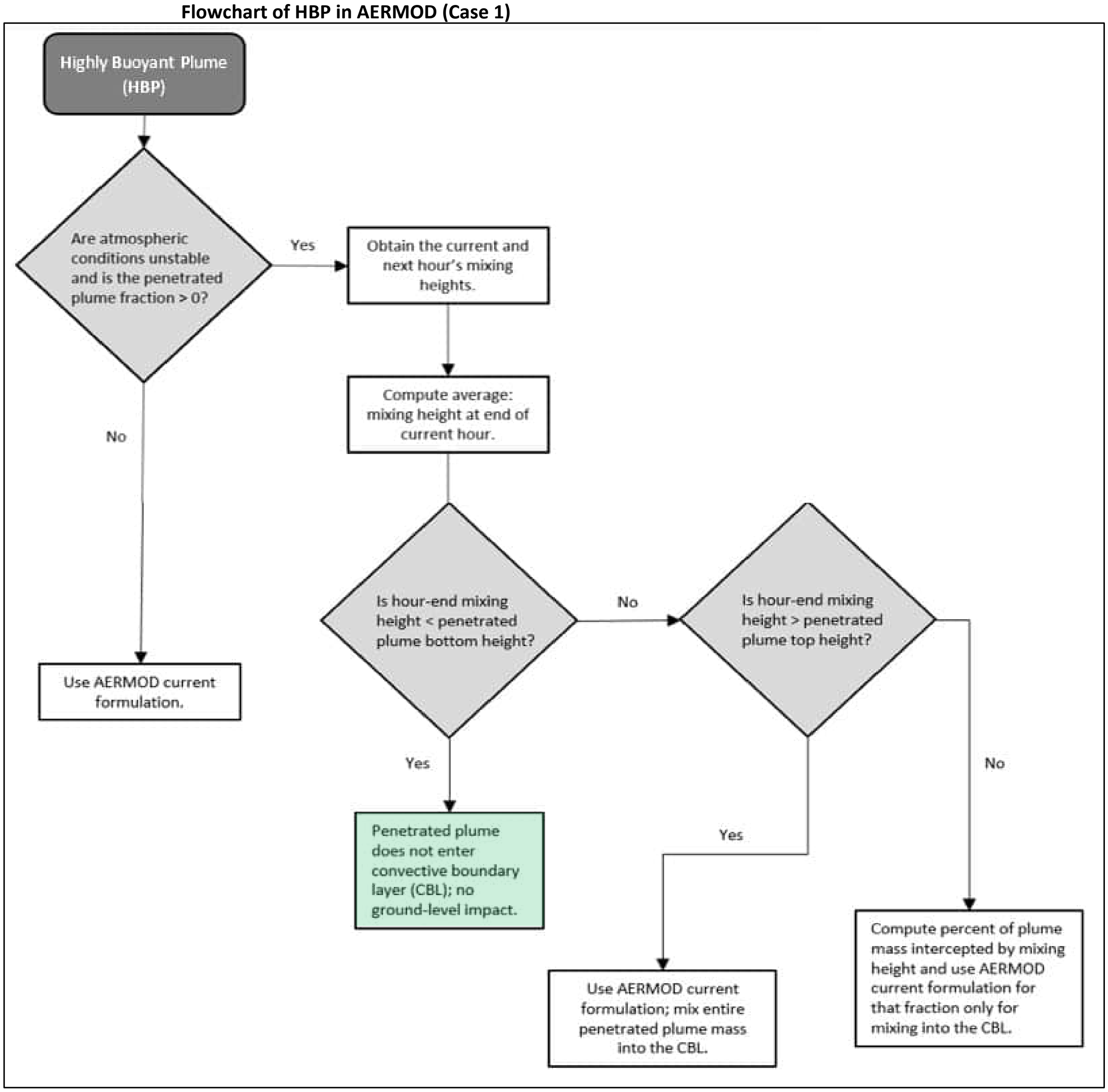
Case 1: **No contribution** of the penetrated plume to the ground-level concentration

Variable in model formulation	Example Value	Units	Parameter in AERMOD	Description
$\overline{z_i}$	500	m	(ZIAVG)	*Height of the mixed layer*
h_{ep}	800	m	(HE3)	*Height of the centerline of the pentrated plume*
σ_{zp}	100	m	(SZ3)	*Vertical dispersion (or spread) of the pentrated plume*
h_{top}	1015	m	(HHTOP)	*Height of the top of the pentrated plume; Centerline + 2.15σ_{zp}*
h_{bot}	585	m	(HHBOT)	*Height of the bottom of the pentrated plume; Centerline - 2.15σ_{zp}*

Since the plume bottom is above the Zi at the end of the hour, **PPFN = 0**.



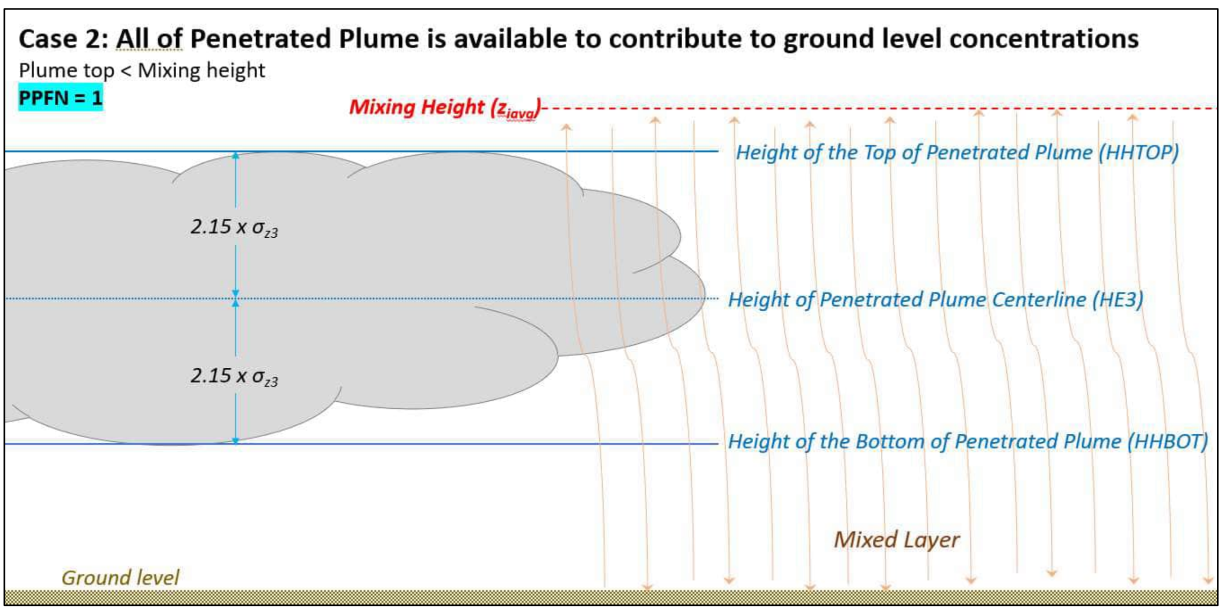
Flowchart of HBP in AERMOD (Case 1)



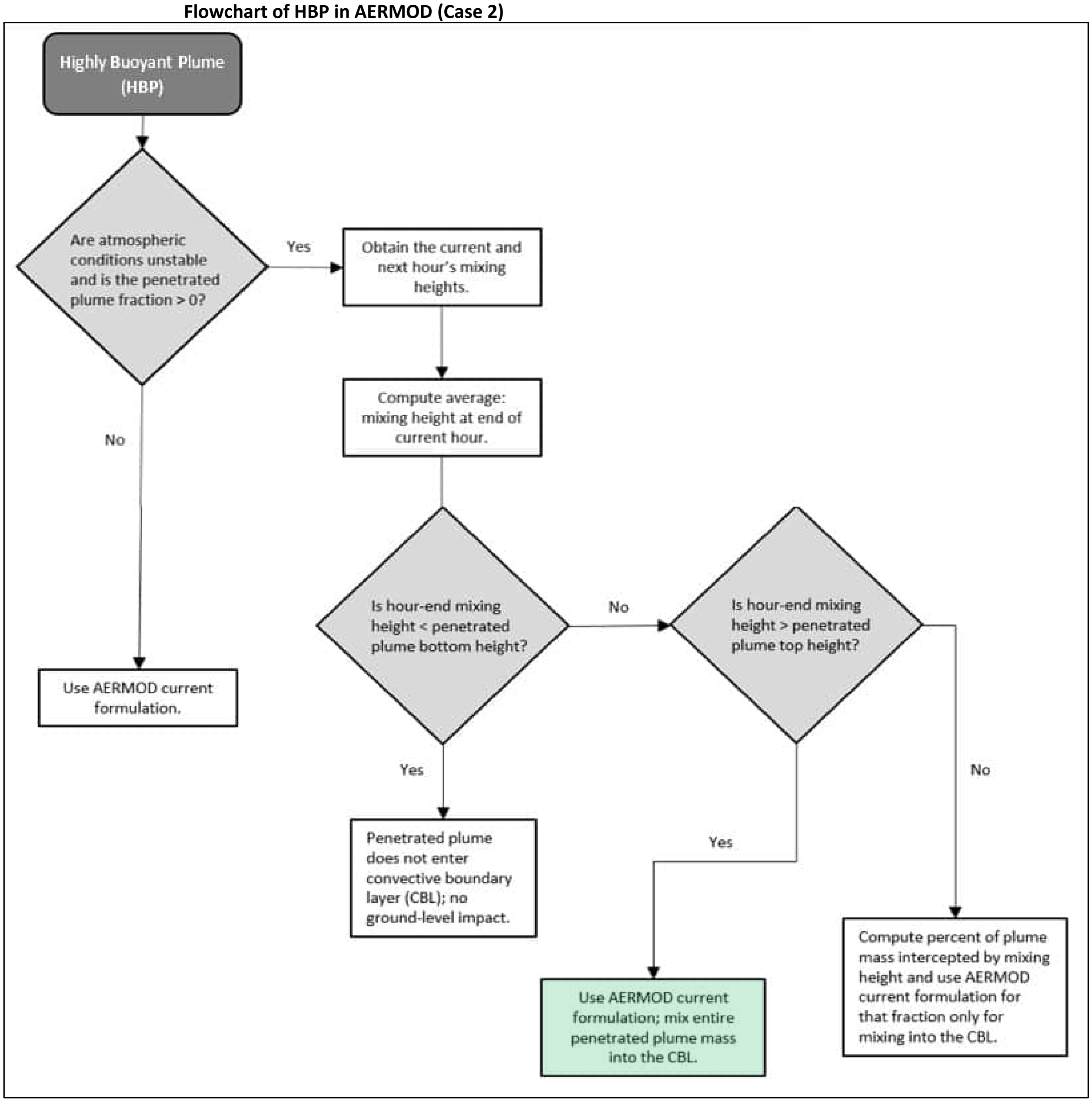
Spreadsheet illustrating the implementation of the HBP formulation (input variables are highlighted in yellow)
Calculations are highlighted in orange.
Case 2: **ALL of the penetrated plume is available** to contribute to the ground-level concentration

Variable in model formulation	Example Value	Units	Parameter in AERMOD	Description
$\bar{z_i}$	1100	m	(ZIAVG)	*Height of the mixed layer*
h_{ep}	800	m	(HE3)	*Height of the centerline of the pentrated plume*
σ_{zp}	100	m	(SZ3)	*Vertical dispersion (or spread) of the pentrated plume*
h_{top}	1015	m	(HHTOP)	*Height of the top of the pentrated plume; Centerline + 2.15*σ_{zp}
h_{bot}	585	m	(HHBOT)	*Height of the bottom of the pentrated plume; Centerline - 2.15*σ_{zp}

Since the plume top is below the Zi at the end of the hour, **PPFN = 1.0**.



Flowchart of HBP in AERMOD (Case 2)



Spreadsheet illustrating the implementation of the HBP formulation (input variables are highlighted in yellow)
Calculations are highlighted in orange.

Case 3a: **Partial contribution** of the penetrated plume to the ground-level concentration (PPFN is between 0.0 and 0.5)

Variable in model formulation	Example Value	Units	Parameter in AERMOD	Description
$\bar{z_i}$	700	m	(ZIAVG)	*Height of the mixed layer*
h_{ep}	800	m	(HE3)	*Height of the centerline of the pentrated plume*
σ_{zp}	100	m	(SZ3)	*Vertical dispersion (or spread) of the pentrated plume*
h_{top}	1015	m	(HHTOP)	*Height of the top of the pentrated plume; Centerline + 2.15σ_{zp}*
h_{bot}	585	m	(HHBOT)	*Height of the bottom of the pentrated plume; Centerline - 2.15σ_{zp}*

ZIAVG is between HHBOT and HE3, so PPFN should be less than 0.5.

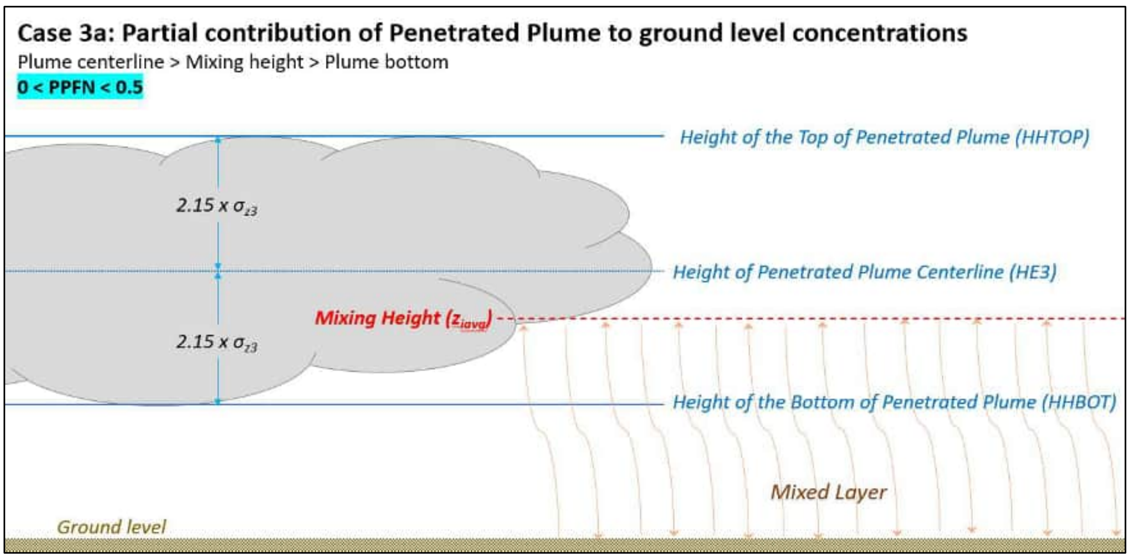
Entrainment adjustment factor (PPFN) Equation in AERMOD:

```
PPFN = 0.5D0*ERF((ZIAVG-HHBOT)/SZ3/DSQRT(2.0D0))
```

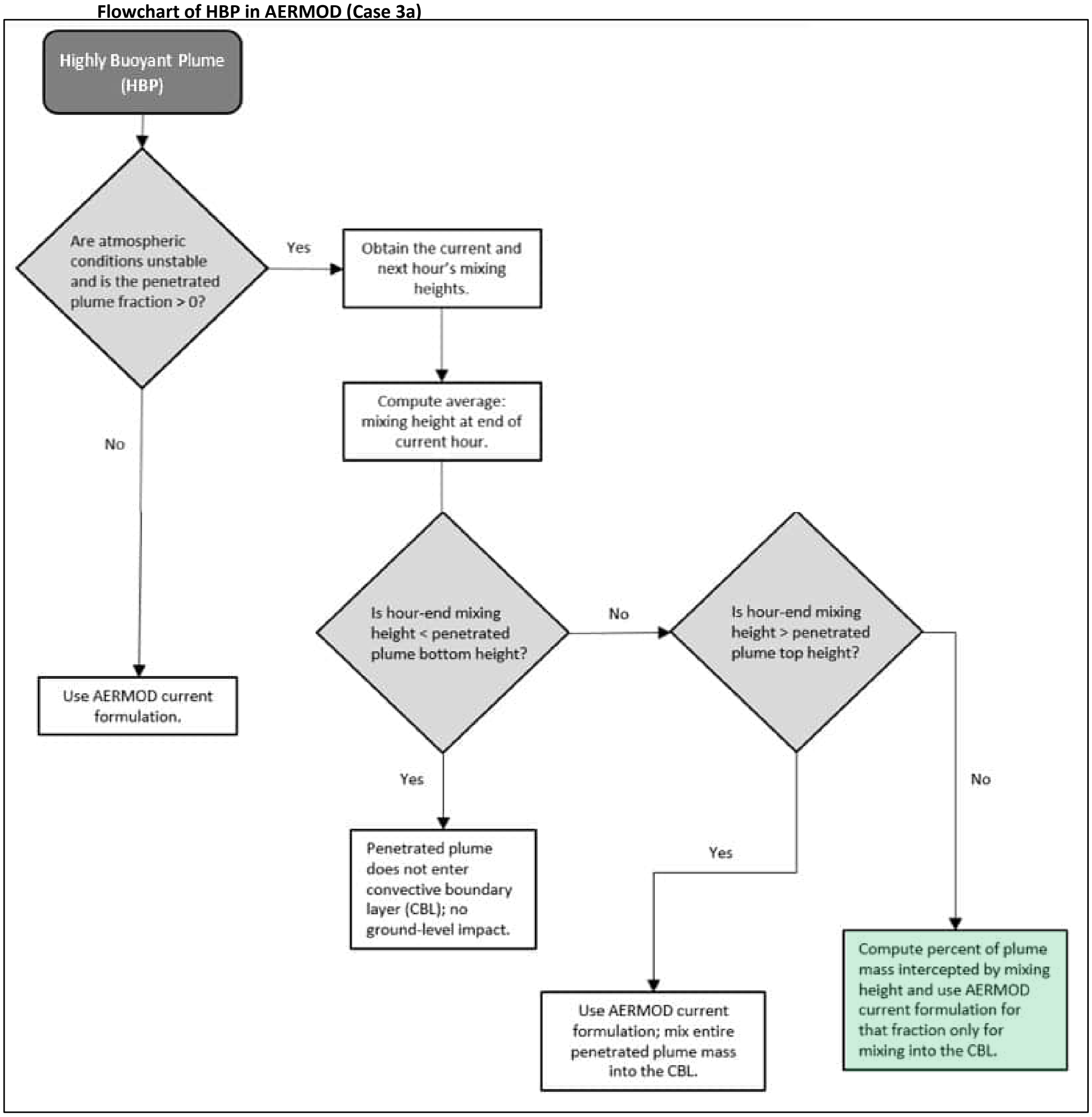
PPFN Equation in model formulation:

$$f_\alpha = \frac{1}{2}\,\mathrm{erf}\left(\frac{\bar{z}_i - h_{bot}}{\sqrt{2}\sigma_{zp}}\right)$$

PPFN:	0.374928



Flowchart of HBP in AERMOD (Case 3a)



Spreadsheet illustrating the implementation of the HBP formulation (input variables are highlighted in yellow)
Calculations are highlighted in orange.

Case 3b: **Partial contribution** of the penetrated plume to the ground-level concentration (PPFN is between 0.5 and 1.0)

Variable in model formulation	Example Value	Units	Parameter in AERMOD	Description
$\bar{z_i}$	900	m	(ZIAVG)	*Height of the mixed layer*
h_{ep}	800	m	(HE3)	*Height of the centerline of the pentrated plume*
σ_{zp}	100	m	(SZ3)	*Vertical dispersion (or spread) of the pentrated plume*
h_{top}	1015	m	(HHTOP)	*Height of the top of the pentrated plume; Centerline + 2.15σ $_{zp}$*
h_{bot}	585	m	(HHBOT)	*Height of the bottom of the pentrated plume; Centerline - 2.15σ $_{zp}$*

ZIAVG is between HE3 and HHTOP, so PPFN should be greater than 0.5.

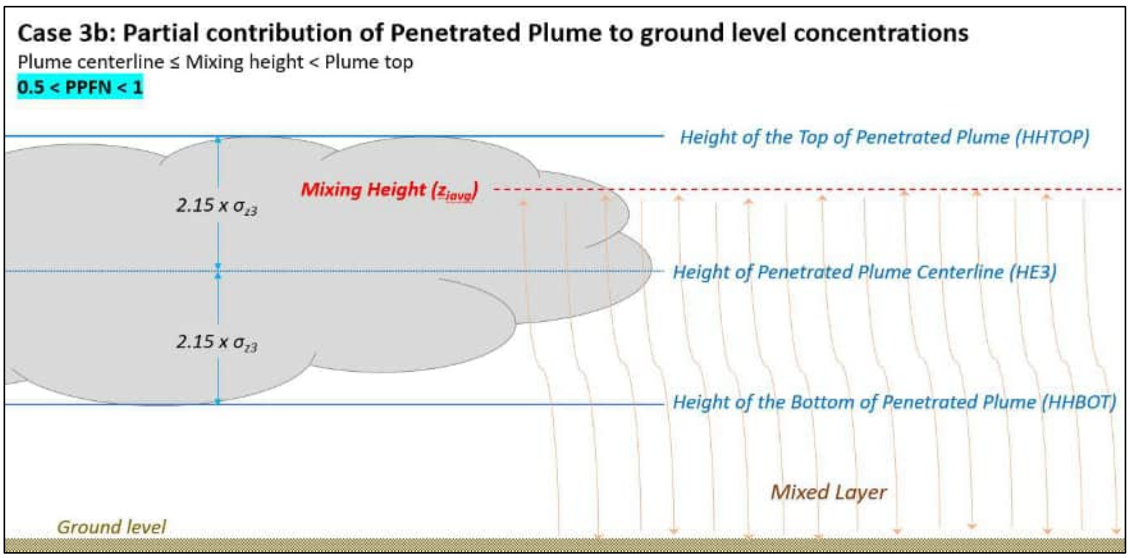
Entrainment adjustment factor (PPFN) Equation in AERMOD:

```
PPFN = 0.5D0*(1.0D0 + ERF((ZIAVG-HE3)/SZ3/DSQRT(2.0D0)))
```

PPFN Equation in model formulation:

$$f_\alpha = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\bar{z}_i - h_{ep}}{\sqrt{2}\sigma_{zp}}\right)\right]$$

PPFN:	0.841345



Flowchart of HBP in AERMOD (Case 3b)