Environment

Prepared for:
American Petroleum Institute and
Utility Air Regulatory Group
Washington, DC

Prepared by:
AECOM
Westford, MA
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AERMOD Low Wind Speed Evaluation Study Results

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Executive Summary

In 2009, AECOM conducted an evaluation of low wind speed databases for short-range modeling applications, with industry sponsorship. The reason for the study was that some of the most restrictive dispersion conditions and the highest model predictions occur under low wind speed conditions, but there has been very little model evaluation for these conditions. The primary aspect of the study involved an evaluation of AERMOD and possible enhancements of that model, as well as an evaluation of CALPUFF. There was also considerable interest and stakeholder involvement in this study on the part of the Clean Air Society of Australia and New Zealand (CASANZ).

Major elements of the study involved the following steps, which were reviewed during the course of the project by EPA/AERMIC:

- a detailed review of available meteorological and tracer evaluation databases, and selection of a qualified subset for use in the actual evaluation work;
- a review of planetary boundary layer parameterizations and evaluation with research-grade meteorological databases;
- determination of various alternative dispersion formulations of AERMOD (and possibly other models such as CALPUFF) to be tested in the evaluation process; and
- completion of the model evaluation work itself, with documentation of model performance results.

In the first phase of the low-wind speed evaluation study, we conducted an evaluation of the prediction by AERMET of a key scaling parameter, u_*. For three diverse field study settings (Cardington, Bull Run, and FLOSS II, over a large range of roughness lengths and seasons), observations from fast-response instruments were used to calculate u_*. We have tested the default AERMET formulations for single-level and two-level approaches, as well as alternative methods for each.

The results of the meteorological evaluation indicate that the alternative methods that we proposed have better performance for u_* (except possibly for FLOSS II, where we show roughly equivalent performance). The results are encouraging to the extent that both the default and the alternative methods were carried forth in the subsequent tracer concentration evaluation testing phase of this project.

An AERMOD evaluation study has been completed that focuses upon low wind speed stable conditions. For the Bull Run field study, where releases were from a tall stack, no high concentrations were observed at ground level during stable conditions. For the Idaho Falls and Oak Ridge field studies, the releases were from low-level sources and very high concentrations were observed during stable conditions. The study has enhanced the evaluation history of AERMOD and provides additional confidence in a possible better performing version of AERMOD that could emerge from this study.

We subsequently conducted evaluations of predictions of tracer concentrations at three sites with the current version of AERMET/AERMOD and with our improved versions (with enhanced u_*) of AERMET/AERMOD. The evaluation results for the tall stack releases in unstable conditions for Bull Run (tall stack release) were found to be acceptable, and do not warrant further AERMOD model development at this time. The current version of AERMOD substantially over-predicted for the Idaho Falls and Oak Ridge low wind stable conditions. However, with inclusion of observed sigma-theta data, incorporation of minimum sigma-v = 0.4 m/s, and with the AERMET improvements to the u_* estimate (as described above), the revised AERMOD model has much improved performance. We also conducted limited evaluations of the CALPUFF model for the Idaho Falls and Oak Ridge databases. The CALPUFF modeling predictions were generally lower than those of AERMOD by roughly a factor of 2. This resulted in CALPUFF underprediction relative to observations for Idaho Falls by about a factor of 2, but less of an overprediction (reduced to about a factor of 2) than that shown by AERMOD for Oak Ridge.

The findings of this study have been forwarded to EPA for consideration in making permanent changes to AERMOD to address its current overprediction tendencies for periods of very low wind speeds in stable conditions.

1.0 Introduction

The need for this study centered on the general recognition that the multiple databases for which AERMOD[1] has been evaluated have not focused upon low wind speeds or low-level non-buoyant sources. Over the past few years, it has been the experience of many model users that these conditions can lead to the highest AERMOD model predictions. This study substantially adds to AERMOD's evaluation for these types of settings, confirming the concentration overpredictions. Revised formulas are suggested that remove much of the AERMOD bias. If the recommended model changes or their equivalent are adopted by USEPA, there would be additional confidence for the modeling community in the regulatory model predictions made for these conditions and source types.

This process has involved the development of interim reports and conference papers for review by various agencies, including USEPA, and the Clean Air Society of Australia and New Zealand (CASANZ). At each step of the way, comments on how to conduct this study have been solicited from USEPA and CASANZ (e.g., evaluation databases, alternative model formulations). Two of the evaluation databases were also used can also be considered for a possible separate evaluation of CALPUFF[2], which is a candidate model for low wind speed applications.

The authors identified several candidate meteorological and tracer evaluation databases and evaluation procedures. Three meteorological databases were evaluated for alternate planetary boundary layer computations for stable conditions, and the results are presented in this report. During early discussions with USEPA, it was strongly recommended that a separate meteorological evaluation be conducted because the results of the meteorological pre-processor, AERMET, are used for AERMOD's concentration predictions for low wind speed conditions.

2.0 Modeling Issues for Low Winds and Low-Level Sources

In 2005, the USEPA promulgated a new dispersion model, AERMOD, which replaced the Industrial Source Complex (ISC) model as the preferred prediction tool for short-range dispersion applications. This development has an important effect upon the determination of New Source Review applications, but also for the compliance status of existing sources. AERMOD is also used to evaluate residual risk, among other applications, where modeling is used to determine the impact of potentially hazardous releases on human health. Any known or suspected prediction biases present with AERMOD could significantly affect the outcome of such modeling analyses.

One suspected area of AERMOD model bias, when compared to other models, is for the situation of very low wind speeds, stable conditions, and near-ground releases. Described below are issues that are worthy of further evaluation, especially in stable conditions.

- There may be very low dilution wind speeds, especially if the low observed wind speeds from a height of 10 meters, as typically used at NWS sites. These speeds are extrapolated by AERMOD using standard wind profile formulas to even lower speeds near ground level. There is no minimum wind speed set in AERMOD for profiling purposes. Note that the effective wind speed used in AERMOD does include a sigma-v component (which can be as low as 0.28 m s^{-1}).

- The model-calculated mechanical mixing height might be very low as wind speed decreases, sometimes well below 10 meters. Buildings and other obstacles to the flow may even be higher than this height.

- The associated model-calculated turbulence levels may be very low, although a meander algorithm attempts to address this issue (but it is not implemented in AERMOD for area sources).

USEPA is aware of the above general concerns with AERMOD, as shown in a presentation[3] made at their 2007 Modelers Workshop. Since the evaluation history of AERMOD is limited for these low wind conditions, USEPA has placed an item on their list of things to do involving AERMOD predictions in light winds. In the presentation made at the 2007 EPA Modelers Workshop, slide 7 indicates the following:

“Revise AERMOD’s treatment of light winds to avoid unrealistically high concentrations.”

While USEPA had this item on its list, it was among many listed in the same presentation. We discussed this issue with USEPA and determined that, at the time of this study, USEPA’s priorities were such that it would not pursue this issue in the near future on their own. Consequently, the authors procured sponsor funds to carry out this study with substantial EPA interaction invited.

There are other developments in the USEPA-provided guidance for meteorological processing that make the need for such a model evaluation more urgent. AERMOD Implementation Guidance released on January 9, 2008 by USEPA narrows the area for determining surface roughness around airport towers. This may increase the likelihood of low wind speeds and low turbulence being used as input to AERMOD because of the low local roughness at airport sites.

USEPA is also aware of the fact that most airports currently do not report wind speeds below 3 knots (about 1.5 m/s), except as “calm”. However, some airport Automated Surface Observing Stations (ASOS) systems are being converted to sonic anemometers, which have a starting threshold of close to zero. In addition, the capability of taking a true average of 60 2-minute running average ASOS winds for the entire hour will likely increase the number of non-calm hours available for input to AERMOD. The wind is less likely to be completely calm for an entire hour than for a specific reading during the hour. Use of data from such observing systems without additional evaluation could increase the importance of low wind speed meteorological conditions and make the issue of possible AERMOD overprediction in low wind speed cases a much more critical issue than it is even now.

3.0 AERMOD Evaluations and Modeling Community Experiences

The model evaluation databases already used for AERMOD heavily emphasized tall stack releases since those emission sources have been the focus of research and funding over the past several decades. Only a few databases, such as Prairie Grass, addressed near-ground sources. Although the AERMOD evaluation databases for the tall stack field experiments contain a few periods of low wind speeds, these did not have a substantial bearing on the outcome of the evaluation studies because peak ground-level concentrations do not generally occur in light wind conditions for tall stack releases. In fact, buoyant releases experience higher plume rises in low winds as opposed to windier conditions, thereby making these conditions even less problematic for the types of sources considered in most of the past model evaluations. The Prairie Grass study involved some light wind cases, but in daytime conditions the releases tended to lift off the ground in light wind convective conditions. In general, the testing of AERMOD for non-buoyant low-level releases in low wind speed conditions was very limited in the EPA evaluation exercises.

Since AERMOD has had widespread use since it was proposed and finally promulgated in 2005, model users have noticed that AERMOD gives higher predictions (sometimes much higher) for low-level releases in stable low wind conditions than models such as ISCST3 or CALPUFF. Some documented reports of these findings are summarized below, in addition to those of the authors.

Rayner[4] of the Department of Environment and Conservation, Western Australia, compared modeled concentrations of AERMOD, ISCST3, and CALPUFF for a volume source under low wind speed conditions. AERMOD results were on the order of 2-3 times higher than the other models. A similar result (AERMOD vs. ISCST3 for ground-level volume sources) was reported by Liebsch and Grimm[5]. Olesen, et al.[6] found that AERMOD over-predicts observations by a factor of 2-3 for the stable low-wind Prairie Grass experiments.

Many modeling investigators, too numerous to mention here, have noted similar differences in AERMOD vs. ISCST3 predictions for low-level, non-buoyant sources.

The next sections describe the databases considered for the evaluation of meteorological formulas in AERMET, provide an overview of the scientific issues, propose modifications to remove biases in AERMET in low wind situations, and discuss the results of evaluations with the revised formulas.

4.0 Meteorological Evaluation Databases

We surveyed the available meteorological databases and selected three field studies with a variety of settings to evaluate AERMOD's meteorological pre-processor for low wind speed, stable conditions. Our specific interest was the prediction of the friction velocity (u_*), which is used in AERMET and AERMOD to estimate wind profiles and turbulent dispersion. The three field studies we selected are:

- Cardington, UK, with an ongoing measurement program (documentation available at http://badc.nerc.ac.uk/data/cardington/).
- Bull Run, Tennessee, USA. 1982 (Bowne et al.[7]).
- Fluxes Over Snow Surfaces, Phase II (FLOSS II), near Walden, Colorado, USA, 2002-3. (National Center for Atmospheric Research – NCAR - documentation available at http://www.eol.ucar.edu/isf/projects/flossii/).

4.1 Cardington

Cardington is a permanent site of surface, sub-surface and mast-mounted instrumentation maintained at Cardington in Bedfordshire by the U.K. Met Office. This site (located at 52° 06' 16" N and 0° 25' 22" W and at an elevation above sea level of 29 meters) is a large grassy, relatively flat field with an open fetch in all directions except the north due to two airship hangars (Figure 4-1). Due to this obstruction, flow from the north was not used in the analysis. Surface roughness, z_o, ranges between 3 and 5 cm. Luhar et al.[8,9] selected the Cardington data for the period August–September and November, 2005. The dataset contains recorded surface measurements timed at 1-, 10- and 30-minute intervals. We have used the 30-minute average observations in this evaluation study.

The meteorological measurements (on a 50-meter tower) included:

1. Three-dimensional sonic anemometers at 10, 25, and 50 m above ground level (AGL).
2. Slow response temperature sensors at 1.2, 10, 25 and 50 m AGL.

Our single-level evaluation conducted with the assistance of Dr. Ashok Luhar of CSIRO (described later in detail) used 10-m data, and the two-level evaluation used 10-m and 25-m data.

4.2 Bull Run

The Bull Run field program was conducted as part of the Electric Power Research Institute's (EPRI) Plume Model Validation & Development project in 1982. The field program was designed to gather concurrent tracer release data along with meteorological and sampling data. This database was used to evaluate and improve existing atmospheric dispersion models primarily used for electric generating facilities. The field program took place at the Bull Run Generating Station (BRGS) characterized by fields and forest near Oak Ridge, Tennessee (Figure 4-2) during the summer/fall of 1982. The terrain is rolling with 50 m to 100 m ridges oriented from SW to NE and spaced about 2 km apart. As seen in the figure, the Clinch River cuts across the terrain near the met towers and next to the BRGS. The field program consisted of two phases. Phase 1 started on July 28th and ended on August 24th. During this period, 19 days of experiments were conducted with each experiment lasting approximately 12-13 hours. Phase 2 started on September 22nd and ended on October 18th. During this period, 19 days of experiments were conducted with each experiment lasting approximately 12-13 hours. An experimentally-determined z_o, of 0.51 m (which is reasonably consistent with an

AERSURFACE predicted value of 0.44 m for the months of August - November) was used for the Bull Run stable hours. The database contains low-wind speed observations under stable and unstable conditions, as well as calculated values of planetary boundary values such as u_* (documented by Hanna and Chang[10]).

The meteorological measurements during the field program occurred at three primary locations as described below. Measurements marked with an asterisk were not utilized for this study.

1. 122-meter tower (located at 36° 00' 49" N and 84° 10' 07" W at and elevation of 251 meters) which observed:
   a) Wind speed, wind direction, and temperature at 10, 30*, 50, 100*, and 122* meters. The 10-meter wind speeds ranged from 0.3 to 2.99 m/s.
   b) Delta-T at 10-50, 10-100*, and 30-122* meters
   c) Dew point at 100 meters*
2. 10-meter tower which observed:
   a) Temperature at 2, 10 meters
   b) Delta-T at 2-10 meters*
3. Central Station which observed:
   a) Atmospheric pressure
   b) Visibility*
   c) Cloud cover
   d) Dew point*
   e) Precipitation*
   f) Surface temperature
   g) Net and solar radiation
   h) Vertical Sounding (Temps, Winds)

Our single-level evaluation used 10-m data, and the two-level evaluation used 10-m and 50-m data. The detailed equations are outlined in later sections.

4.3 FLOSS II

FLOSS II is the second phase of the FLOSS (Flow over Snow Surfaces) project that was designed by NCAR to study surface meteorology over snow-covered rangeland. The FLOSS II experiment was conducted in the North Park region of Colorado, near Walden, CO during the winter of 2002/2003. Phase II of the FLOSS experiment began collecting data in November of 2002 with data collection ending in April of 2003. The measurements are 60-minute averages.

FLOSS II consisted of three measurement sites, whose locations are shown in Figure 4-3. Figure 4-4 shows a panoramic view of the Medicine Bow Mountains looking east from the FLOSS Site. The primary measurement site (located at 40° 39' 32" N and 106° 19' 26" W at an elevation of 2476.5 meters) consisted of a 34-meter walk-up tower (see Figure 4-5) and was equipped to measure the following parameters relevant to our evaluation:

- profiles of mean air temperature and RH at 0.5, 1, 2, 5, 10, 15, 20, and 30 m
- profiles of three-component winds at 1, 2, 5, 10, 15, 20 and 30 m
- nearby radiation stand with up-and-down-looking long wave radiometers at 4 m and down-looking long wave radiometer at 1.5 m.

The land use surrounding the FLOSS II experiment site could be considered relatively barren with some sage grass, and a relatively low surface roughness (0.5 cm). Additionally, during the experiment, a light snow cover was also present. The terrain surrounding the area was relatively flat. Figure 4-6 provides a depiction of the terrain surround the FLOSS II measurement sites. Our single-level evaluation used 10-m data, and the two-level evaluation used 10-m and 30-m data.

Figure 4-1: Composite Photo of Cardington Field Site, Meteorological Tower and Airplane Hangars.

Photo credit courtesy of http://badc.nerc.ac.uk/data/cardington/

Figure 4-2: Aerial Photo of Meteorological Tower for Bull Run, Oak Ridge, TN.

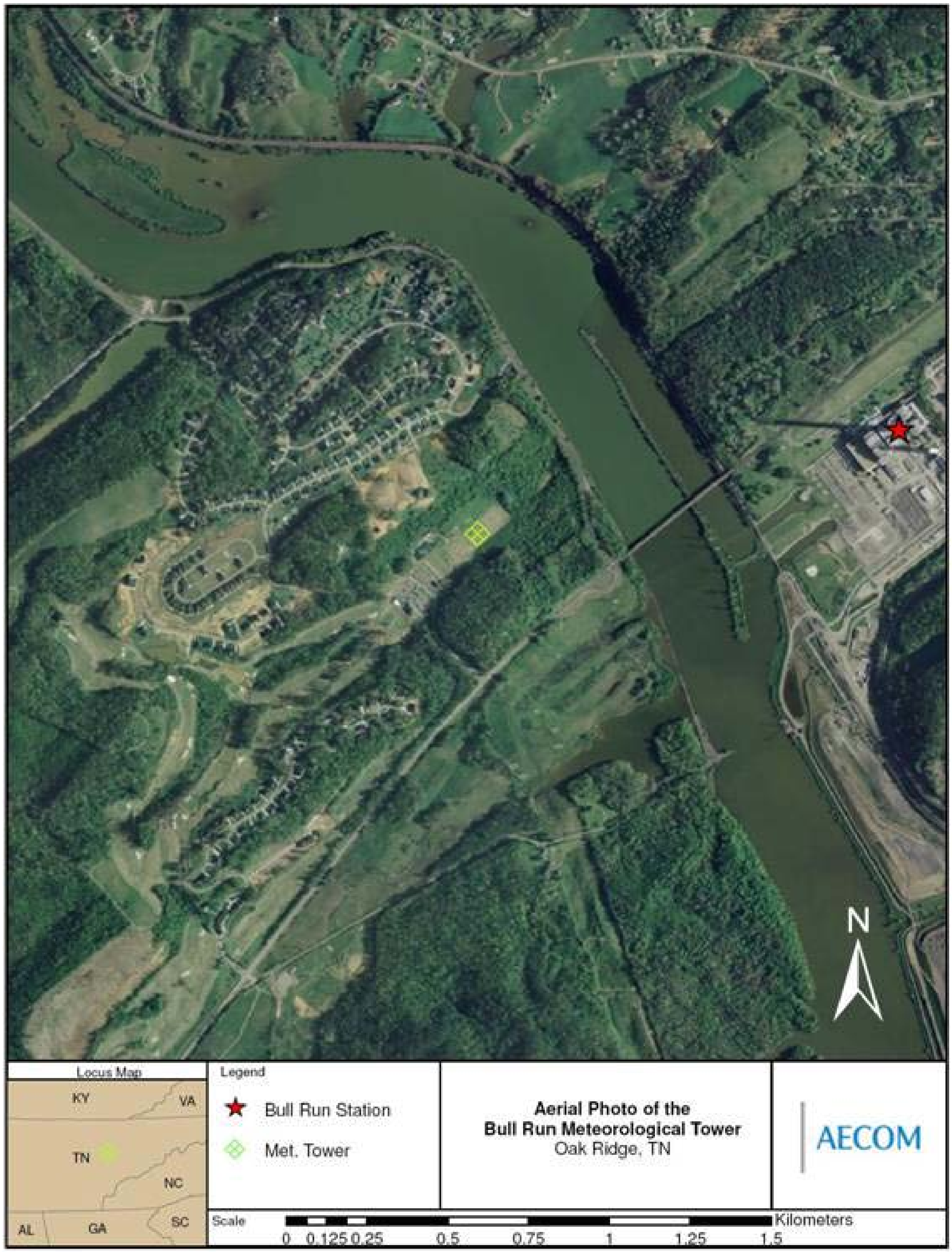


Figure 4-3: Location of the FLOSS II Measurement Sites

Courtesy of Steven Oncley, NCAR Research Technology Facility (http://www/eol..ucar.edu/isf/projects/fossil/)

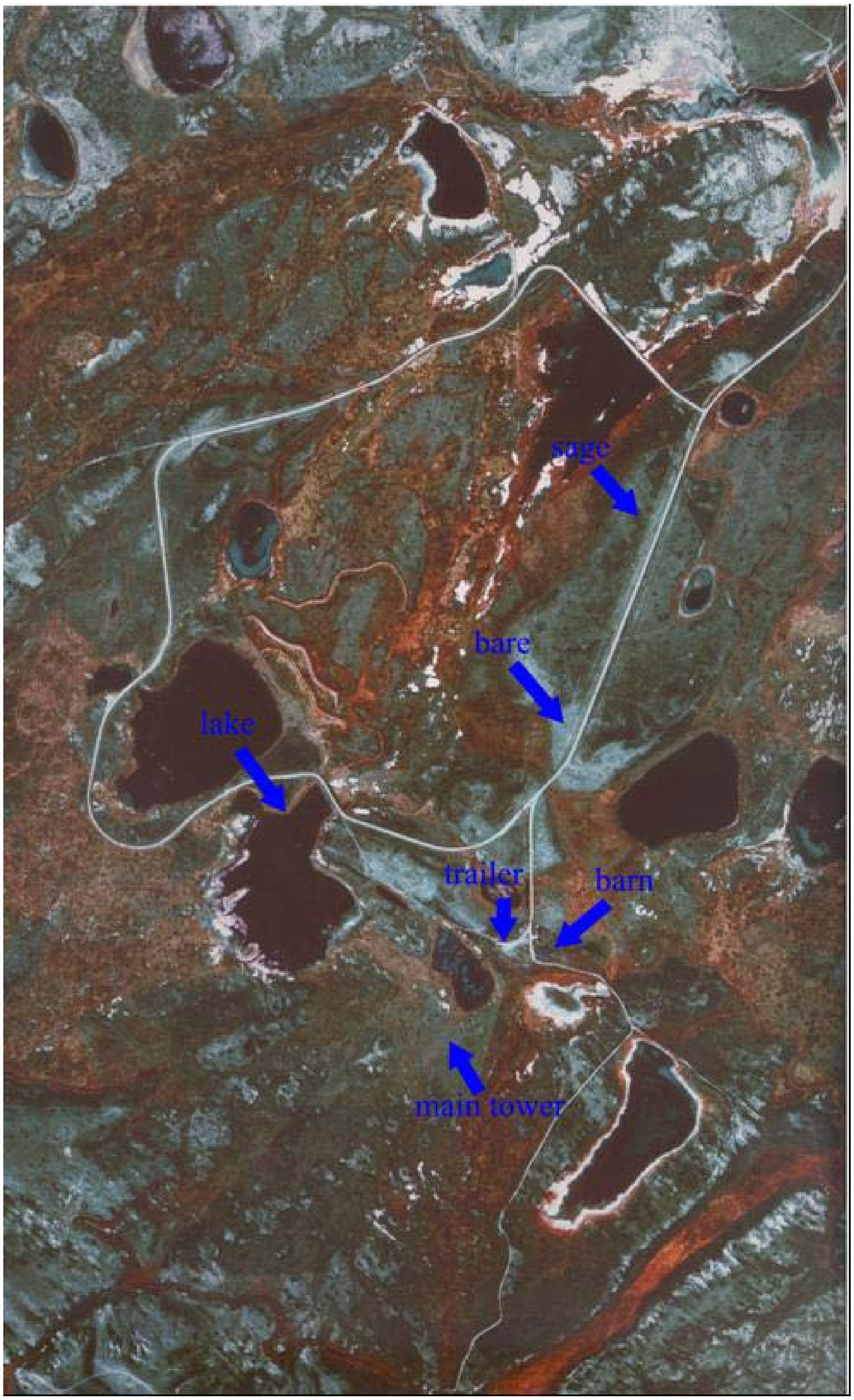


Figure 4-4: Looking East Toward Medicine Bow Mountains from FLOSS II Site

Courtesy of Steven Oncley, NCAR Research Technology Facility (http://www/eol..ucar.edu/isf/projects/fossil/)

Figure 4-5: FLOSS II 34-Meter Walk-Up Tower

Courtesy of Steven Oncley, NCAR Research Technology Facility (http://www/eol..ucar.edu/isf/projects/fossil/)

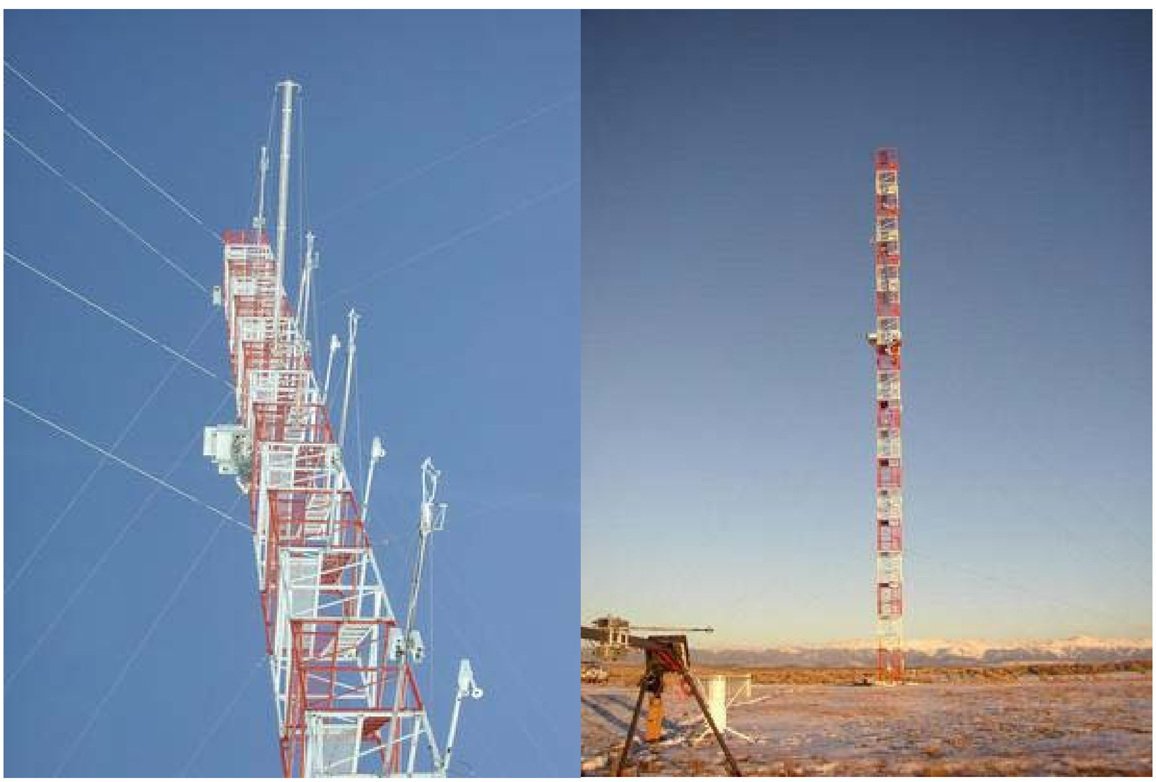
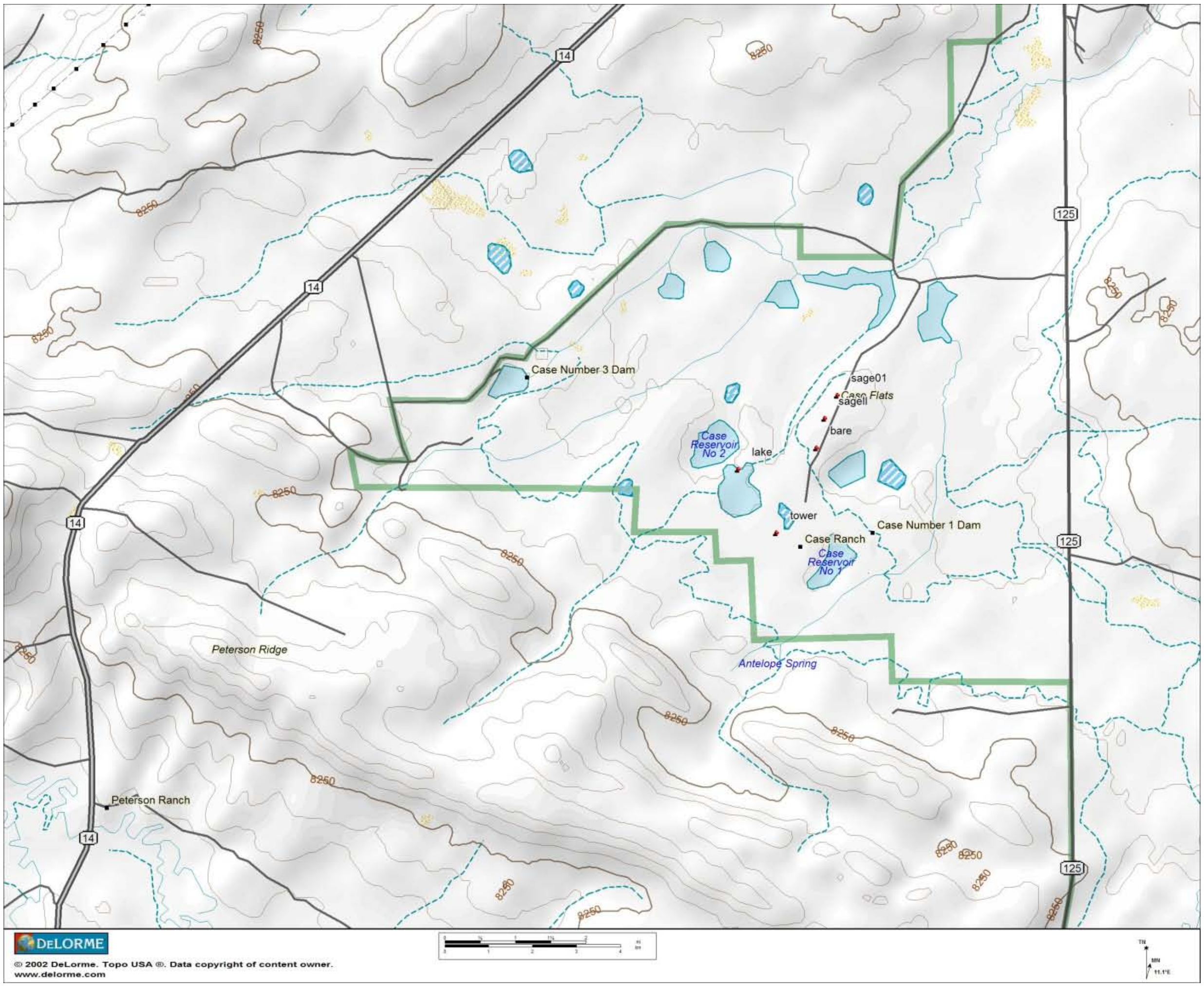


Figure 4-6: Terrain Surrounding the FLOSS II Measurement Sites (50-ft Contour Intervals)

Courtesy of Steven Oncley, NCAR Research Technology Facility (http://www/eol..ucar.edu/isf/projects/fossil/)



5.0 Meteorological Evaluation Procedures

5.1 Data Preparation

This study evaluated the predictions of PBL meteorological parameters used by AERMOD, with focus on the friction velocity, u_*. The specification of u_* is quite important in AERMOD especially for low-level, non-buoyant sources because of the following model dependencies:

- the calculated mechanical mixing height during neutral or stable conditions is proportional to u_* raised to the 1.5 power
- the calculated standard deviations of mechanical turbulence (for both lateral and vertical components) near the ground are proportional to u_*. The rate of dispersion is thus dependent on u_*.
- the calculated wind speed u at levels other than the observation level are proportional to u_*
- the calculated MO length, L, is a function of u_*.

Underpredictions of u_* will lead to a calculated mechanical mixing height that is too low and dispersion that is too restrictive. Such conditions could lead to concentration overpredictions from low-level, non-buoyant sources. AERMET calculates u_* and the Monin-Obukhov length, L from meteorological data that contains wind and temperature measurements at either one or two levels.

The observed values of u_* were already in the Bull Run data set, but needed to be calculated for FLOSS II using sonic anemometer observed co-variances:

$$u_* = \left(\left(\overline{w'u'}\right)^2 + \left(\overline{w'v'}\right)^2\right)^{0.25} \qquad (1)$$

where w' is the vertical velocity fluctuation and u' and v' are the zonal (west to east) and meridional (south to north) velocity fluctuations, respectively. The scaling temperature, θ* is expressed as

$$\theta_* = \frac{-\overline{w'\theta'}}{u_*} \qquad (2)$$

where θ' is the potential temperature fluctuation.

We did not directly evaluate the Cardington database because the UK Met Office would not release this database to us without payment of a fee. Instead, we relied upon Dr. Luhar's independent evaluation with code modifications that we supplied to him. For that reason, the evaluations for Cardington can be considered as a "hands-off" independent evaluation. We did process the data for the Bull Run and FLOSS II data sets, and excluded non-stable hours from the evaluation. The criteria for excluding a period from the evaluation included periods with

a) any missing wind speed, direction or temperature at any level being considered by the one-or-two-level method;

b) missing cloud cover data;

c) absolute temperature decreasing with height; or

d) positive net radiation (i.e., non-stable).

Criteria (a) – (c) were already considered in the Cardington evaluation by Luhar. For the Bull Run and Floss II analysis, the criteria were modified. Missing wind or temperature data from only the two selected levels caused a period to be excluded. Criterion (d) was added in order to restrict the study to nocturnal hours, hence excluding convective activity. Finally the hourly air densities were calculated (as opposed to a constant density assumed by Luhar for the Cardington database). The differences produced by this latter task in u_* and θ_* were insignificant.

5.2 Formulations that were Evaluated

The default AERMET method for computing the planetary boundary layer variables such as u_* is the single-level method that requires cover input to parameterize stability. AERMET also assumes that, in the absence of representative cloud cover measurements, a two-level method (the Bulk Richardson number, Ri, method) may be used, which requires two levels of temperature data.

In addition, we tested alternatives to both the single-level and two-level AERMET methods in this study. Our revision to the single-level method involved a minor adjustment to the transition point (critical wind speed) between the near-zero wind speed part of the formulation and the higher wind speed part, as described below. Our revision to the two-level (Bulk Richardson number) method extends upon the work initiated by Luhar and Rayner[9] in their analysis of the Cardington site. We did not test Luhar and Rayner's alternative single-level method based on the standard deviation of temperature since this parameter was not reported at either the Bull Run or FLOSS II sites, and it is rarely measured in the United States.

AERMET's single-level and two-level methods, as well as the alternative methods, were applied to both the Bull Run and Floss II data sets. The single-level alternative method focused upon altering the transition point for stable conditions for calculated u_* values between the linear (near-zero wind speed regime) and quadratic solution (higher wind speed regime). This transition or inflection point represents the critical wind speed, u_{crit} such that for u values above u_{crit}, a quadratic solution for u_* is used that is based on solution of the fundamental boundary layer equations. Below u_{crit}, the AERMET developers simply assumed that there was a linear decrease in u_* as u approaches 0.0. This latter assumption is subjective (i.e., based on scientific common sense) and is not derived from basic theory. The critical wind speed is the value above which real solutions exist to the quadratic solution, which is presented in the AERMOD Model Formulation Document[11] (Equation 15 in that document) and is defined as

$$u_{crit} = \frac{2u_0}{C_D^{1/2}} \qquad (3)$$

where $$u_0^2 = \frac{\beta z g \theta_*}{T} \qquad (4)$$

and where the constant β = 5 (from the Monin-Obukhov Similarity Theory (MOST) stable wind speed formula), z is the measurement height; T is the temperature in K at the surface; and g is the acceleration due to gravity (9.8 m/s^2).

C_D, the drag coefficient for neutral conditions, is defined as

$$C_D = u_* / u(z) = \frac{\kappa}{\ln\left(\frac{z}{z_0}\right)} \qquad (5)$$

where κ is the von-Karman constant (=0.4); and z_o is the surface roughness length.

Note that u_{crit} is proportional to $(z \ln(z/z_o))^{1/2}$. Thus, as the measurement height increases, so also does u_{crit}. This means that, for large measurement heights, u_* is being estimated by the linear interpolation formula for a larger range of wind speeds.

In order to have an estimate of u_* when $u < u_{crit}$, AERMET uses a simple linear formula:

$$u_*/u_*(u_{crit}) = u/u_{crit} \quad . \qquad (6)$$

In AERMET, the two solutions of u_* for the single-level method at wind speeds above and below the critical wind speed produce different slopes. This is shown in Figure 5-1 for a variety of surface roughness values. It is seen that a “jump” in the slope occurs over a narrow range of speeds just above u_{crit}. For the Bull Run and FLOSS II data sets (Figures 5-2a-b), calculated values of u_* (blue crosses) based on sonic anemometer observations reveal that the current single-level method does not properly capture the range of u_* in the domain below u_{crit} as a result of the “jump” in u_* at u slightly above u_{crit}. An obvious easy way to fix this is to have the linear regime start at a u_{crit} which is about 0.5 to 1.0 m/s higher than the current value.

The underprediction of the unmodified single-level method in AERMET appears at low wind speeds during stable conditions for a range of cloud cover conditions (bold, dotted and thin lines in Figures 5-2a and b). In our revised single-level method, we changed the transition value of the wind speed slightly so that the linear dependence of u_* on u starts at 1.25 times the calculated u_{crit}. Thus we still use equation (6) but substitute 1.25 u_{crit} for u_{crit}. This adjustment appears to eliminate the change in slope of u_* versus u between the linear and quadratic solutions, while better matching observed u_*, particularly in the Bull Run set (red dots in both Figures 5-2a and b). Note that the 1.25 factor may need further adjustment in the future as more field data sets are analyzed.

For the two-level method, Luhar and Rayner[9] developed an alternative stability function for determining PBL parameters such as u_* in low wind conditions. They suggested the use of an alternative stability function for momentum under low wind conditions, which involves a transition in the wind speed profile at a certain threshold stability value ($(z/L)_c = \zeta_c = 0.7$), above which the following expression is used:

$$u_* = \frac{\kappa u}{\alpha\left[\zeta^{\beta}\left(1+\gamma\zeta^{1-\beta^*}\right) - \zeta_0^{\beta}\left(1+\gamma\zeta_0^{1-\beta^*}\right)\right]} \approx \frac{\kappa u}{\alpha\left[\zeta^{\beta}\left(1+\gamma\zeta^{1-\beta}\right)\right]} \qquad (7)$$

$$\theta_* = \frac{\kappa(\theta_2 - \theta_1)}{\ln\left(\frac{z_1}{z_2}\right) + \frac{\beta(z_2 - z_1)}{L}} \qquad (8)$$

$$L = \frac{T u_*^2}{\kappa g \theta_*} \qquad (9)$$

with ζ=z/L, a stability factor; ζ_0 the stability factor based on z_0; the constants α=4, β*=0.5, and γ=0.3; θ_i is the potential temperature of the *i*-th level; z_i is the height of the *i*-th level; and L is the Monin-Obukhov length. Thus, it is apparent from (8) and (9) that θ_* and L must be solved iteratively due to their mutual dependence. In their analysis of the Cardington dataset, Luhar and Rayner contributed to the reformulation of (7) which, in turn, affected the subsequent calculation of θ_* and L.

Our further modifications to this method included:

a) Using a threshold for z/L = ζ =0.4 rather than 0.7 as discussed above, based upon a range of possible values discussed by Luhar and Rayner[9]. With this semi-empirical choice, particularly for the Bull Run data set, the alternative equation covered more cases and therefore provided better agreement with observations. For hours with values of ζ < 0.4, the formulation defaulted to the AERMET method, which uses the bulk Richardson number.

b) Using the full rather than the approximate solution for u_* in (6) appeared to improve the prediction of u_*.

c) Introduction of a “hybrid” Luhar two-level method provides a backup value in cases when the iterative scheme does not properly converge. In these cases, the hybrid method will use the AERMET initial calculation for u_*, θ_* and L and then solve u_* using

$$u_* = \frac{\kappa u}{\left[\ln\left(\frac{z}{z_0}\right) + \frac{\beta z}{L}\right]} \qquad (10)$$

and θ_* using equation (8).

Figure 5-1: AERMET Predicted u_* Based on the Single-Level Method as a Function of Wind Speed, u, and Varying Surface Roughness values z_o

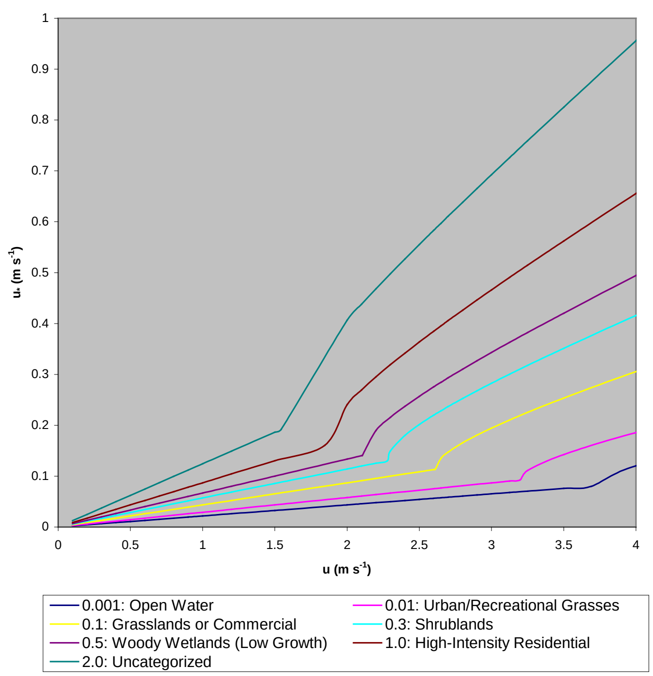
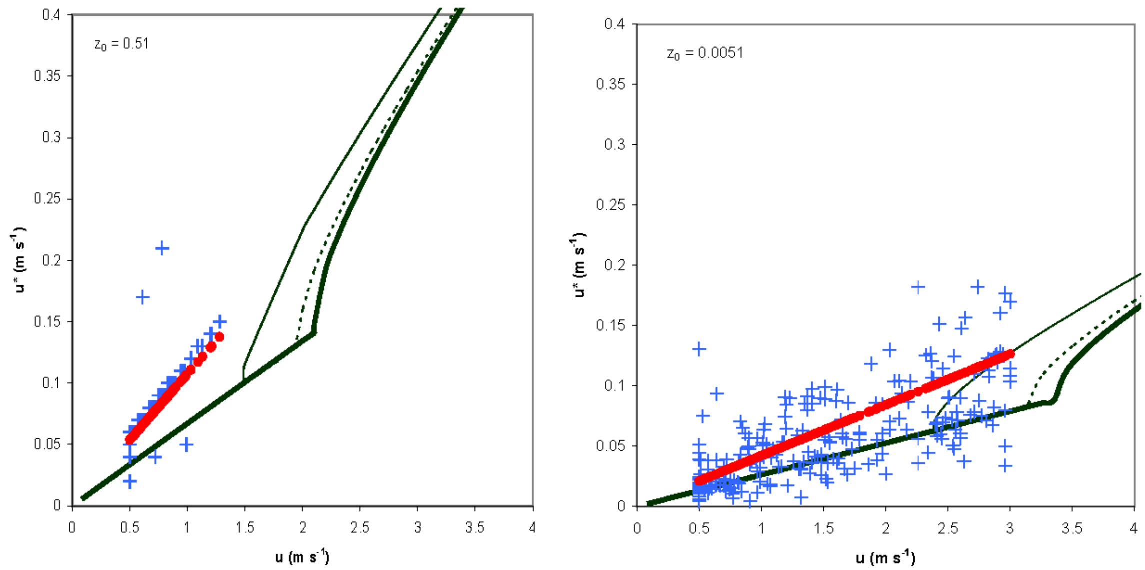


Figure 5-2: Comparison of Low Wind Speed u vs. u* for (a) Bull Run and (b) FLOSS II

Adjusted single-level calculated values shown in red dots, and the observed values is blue crosses. The solutions for the quadratic solutions include clear (bold line), 50% cloud cover (dotted), and fully overcast (thin).



6.0 Meteorological Evaluation Results

The evaluations described below are based primarily on visual inspection of scatter plots of observed and predicted u_*, and box and whisker plots of the ratio of predicted to observed u_*. Some quantitative calculations of mean bias in the ratio of predicted to observed u_* at low wind speeds (< 3.0 m/s) are shown in Table 6-1.

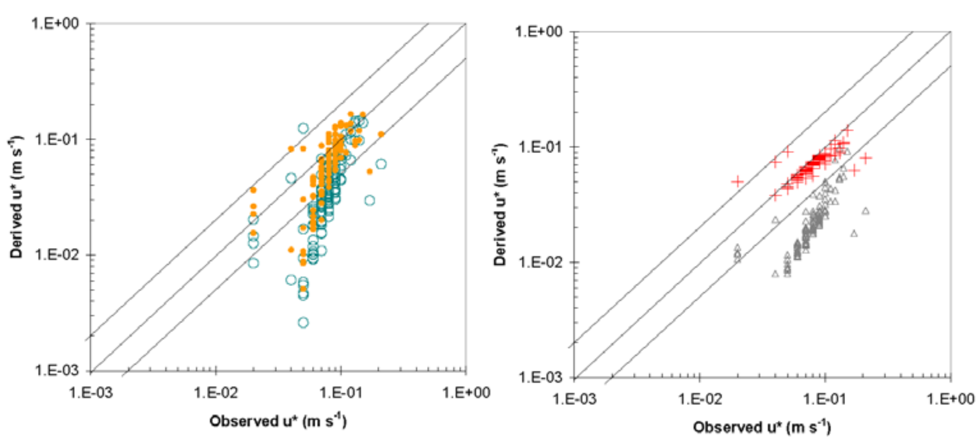
While the modified single-level method provides a direct solution for u_*, the two-level method requires an iterative method to calculate u_* and θ_*. Our focus was on u_*, which is used in AERMOD for computation of the nocturnal mixing height and turbulence parameters. Figure 6-1 is a scatter plot comparing the computed and observed values for u_* for various two-level methods for the Bull Run database. In Figure 6-1a, the full version of equation (7) generates predicted u_* values closer to observed u_* for the Bull Run data set than those using the approximated equation (7). Figure 6-1b compares AERMET-predicted values for u_* with the hybrid version of the Luhar method. As shown in Table 6-1, the hybrid Luhar scheme greatly improves the accuracy of the u_* values with respect to AERMET values.

Similar scatter plots are presented for FLOSS II in Figure 6-2. We note that the difference between the full and approximated Luhar two-level equations is minimal for this database with a low surface roughness. Figure 6-2b shows a general improvement over AERMET for the hybrid Luhar method in predicting u_*, especially for lower wind speed cases.

The improvement over AERMET of the hybrid Luhar method, especially for the lower wind speeds, is evident in the plots shown in Figure 6-3, which shows the behavior of u_* vs. u (prediction methods as well as observations) for wind speeds below 3 m/s for Bull Run and FLOSS II.

Figure 6-1: Comparison of Bull Run Observed vs. Predicted (a) and (b) Frictional Velocity, u_*, for Various Two-Level Methods

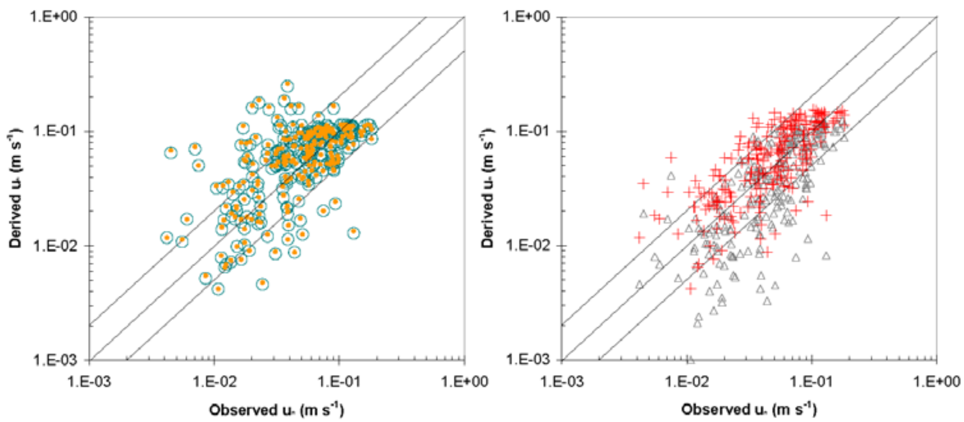
Plot (a) compares the Luhar two-level predicted values using the approximated (dark green) and full (orange) versions of equation 7. Plot (b) compares the hybrid Luhar two-level method (red) against the current (unmodified) AERMET predictions (grey).



(a) u* Luhar two-level methods (b) u* Hybrid Luhar vs. AERMET

Figure 6-2: Comparison of FLOSS II Observed vs. Predicted Frictional Velocity, u_*, for Various Two-Level Methods

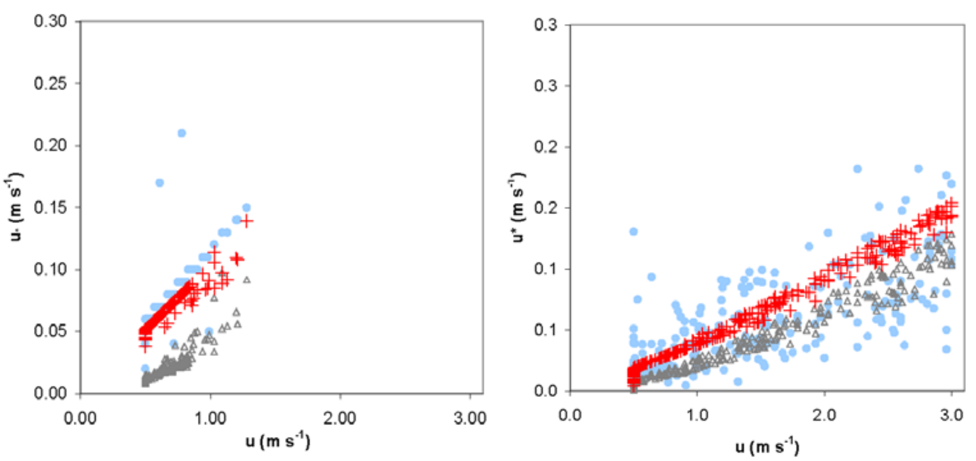
Plot (a) compares the Luhar two-level predicted values using the approximated (dark green) and full (orange) versions of equation 7. Plot (b) compares the performance of the hybrid Luhar two-level method (red) against the current (unmodified) AERMET (grey). Results are shown for observations with wind speeds less than 3 m/s.



(a) u* Luhar two-level methods (b) u_* Hybrid Luhar vs. AERMET

Figure 6-3: Comparison of u vs. u_* for (a) Bull Run and (b) FLOSS II

The hybrid Luhar two-level calculated values are shown in red crosses; the current (unmodified) AERMET values in grey triangles; and the observed values in blue dots.



(a) Bull Run (b) FLOSS II

A comparison of the observed and calculated values of u_* reveals the limitations of and improvements upon the current AERMET under low wind, stable conditions for both the single and two-level methods. In Figures 6-4 through 6-6, left-hand plots (a) and (c) represent the current single and two-level AERMET predictions, respectively, whereas right-hand plots (b) and (d) represent the enhanced single-level and two-level hybrid Luhar method using the full version of equation (7). For each site, the underprediction of the current AERMET scheme is readily apparent in the left-hand plots (Cardington, Figure 6-4; Bull Run, Figure 6-5; and FLOSS II, Figure 6-6). For Bull Run and FLOSS II, the modifications in both formulations positively shift and reduce the bias in the predicted u_* values

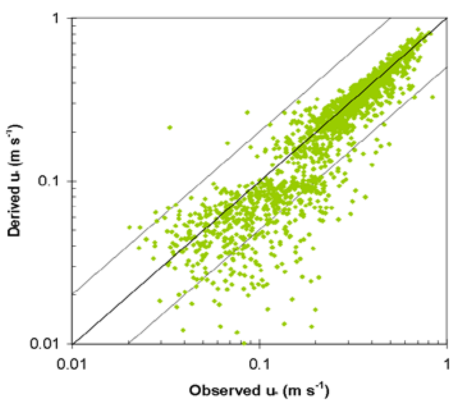
(Table 6-1). This shift compensates for the tendency in AERMET to under-predict the frictional velocity.

Cardington and Bull Run have higher (and more typical) roughness lengths than FLOSS II, and hence provide an opportunity for further assessing the accuracy of the modifications made. In both cases, implementation of the enhanced methods (for both single and two-levels) corrects the underprediction tendency for u_*. The large sample size of the evaluated data periods for Cardington provides additional confidence to the evaluation results. Additionally, the Bull Run results provide distinct and clear support of the improvements to the predictability of both enhanced methods.

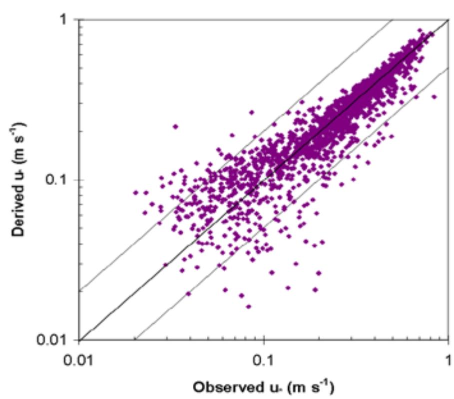
The measured meteorological conditions at FLOSS II occurred during the winter over terrain with a much lower surface roughness (z_0 = 0.005) than the other two sites. The predicted u_* values for FLOSS II (Figures 6-6a-d) were not as clear as the Bull Run data set in supporting the improved accuracy of the enhanced methods. This may be due to the smaller discontinuity in the u_* curve. The revised method does result in an increase in the values predicted for u_*. The improvement in performance for the u_* predictions across diverse data sets and roughness settings is encouraging.

Figure 6-4: Comparison of Observed and Predicted Fictional Velocity, u_* for Cardington.

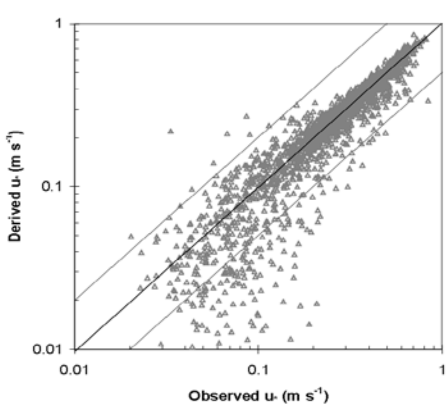
Single-level, current AERMET (a); single-level, modified AERMET (b); two-level, current AERMET (c); two-level, hybrid Luhar (d). The factor-of-two lines are shown.



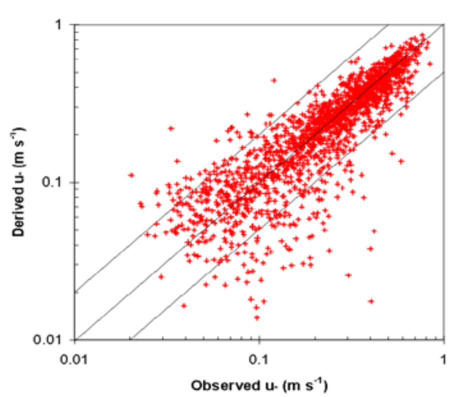
(a) Current AERMET, Single-level



(b) Modified AERMET, Single-Level



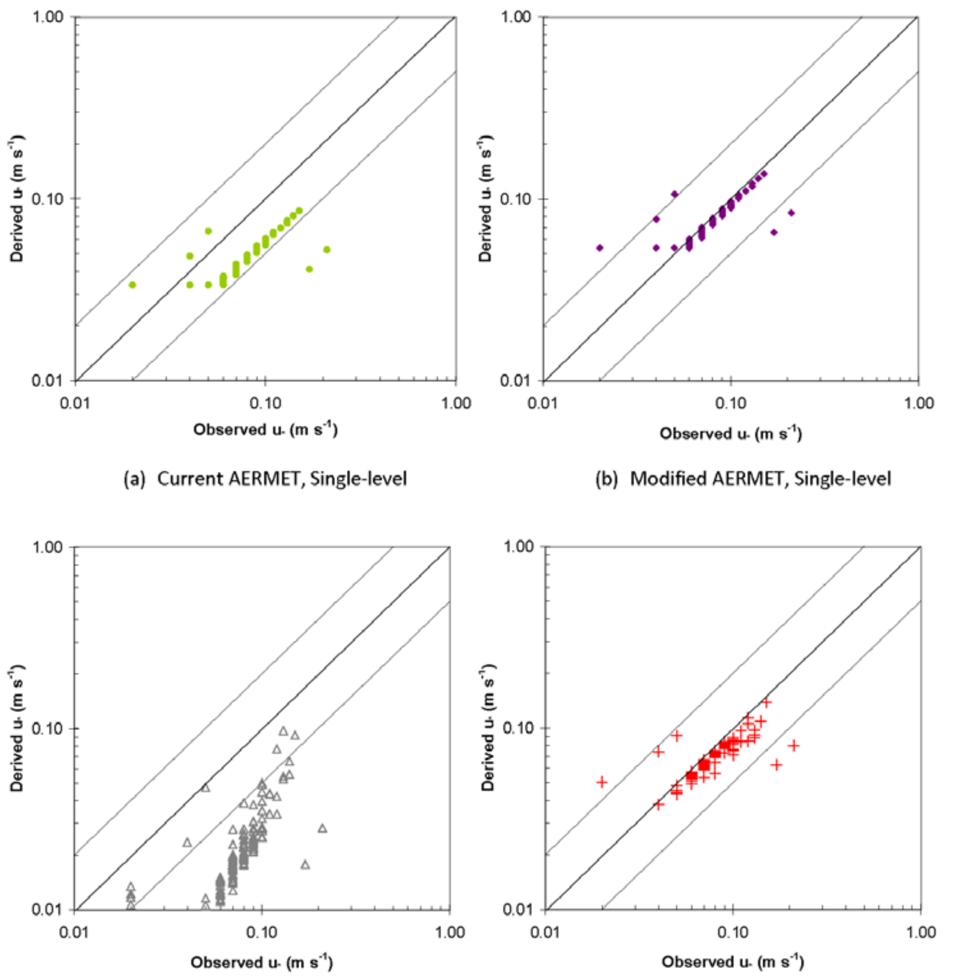
(c) Current AERMET, two-level



(d) Hybrid Luhar, two-Level

Figure 6-5: Comparison of Observed and Predicted Friction Velocity u* for Bull Run.

Single-level, current AERMET (a); single-level, modified AERMET (b); two-level, current AERMET (c); two-level, hybrid Luhar (d). The factor-of-two lines are shown.



(a) Current AERMET, Single-level

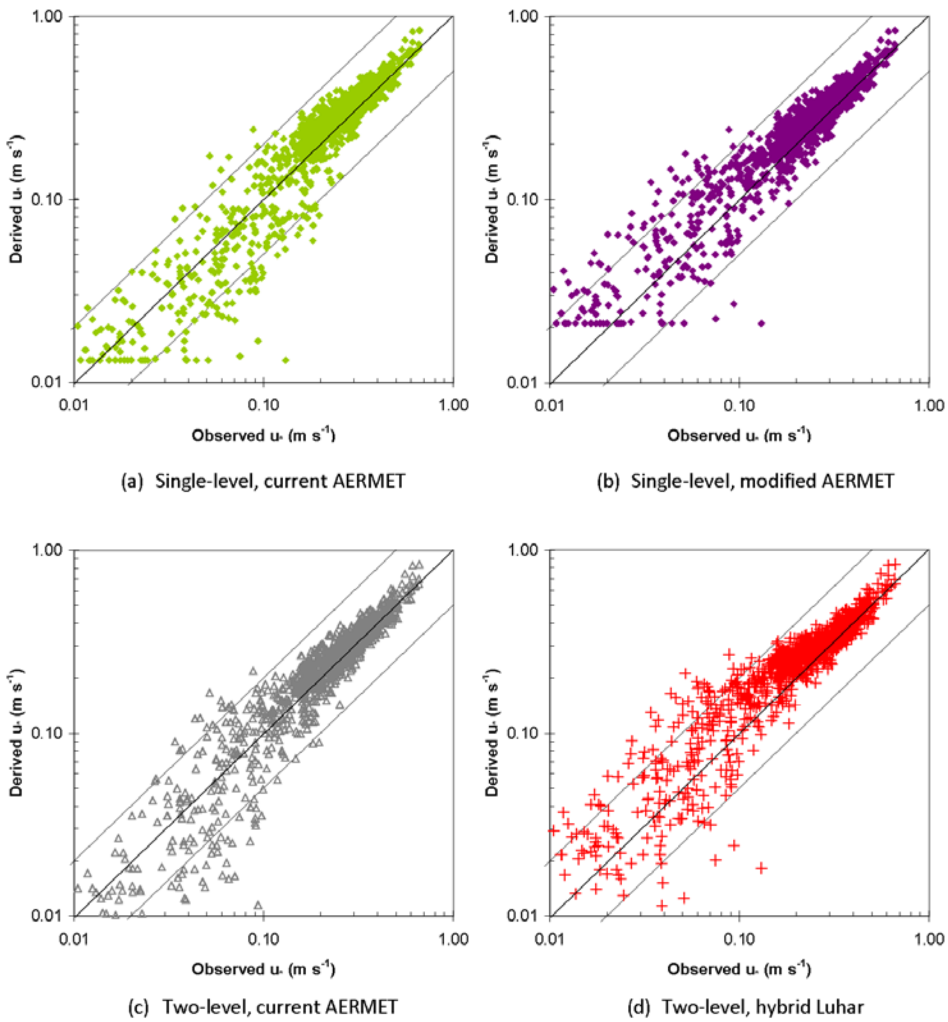
(b) Modified AERMET, Single-level

(c) Current AERMET, Two-level

(d) Hybrid Luhar, Single-level

Figure 6-6: Comparison of Observed and Predicted Frictional Velocity, u* for FLOSS II

Single-level, current AERMET (a); single-level, modified AERMET (b); two-level, current AERMET (c); two-level, hybrid Luhar. The factor-of-two lines are shown.



In Figure 6-7, box and whisker plots for the ratio of predicted to observed u* for each of the sites show the improvement of the revised methods for low wind speed conditions (< 3.0 m s^{-1}) at the Cardington and Bull Run sites (Figures 6-7a and b, respectively). The enhanced single-level and the Luhar two-level hybrid methods both have geometric mean biases of less than about 10 % (i.e., percentage different from 1.0), with distributions equally spread about the ratio of 1.0. For the FLOSS II field site, the geometric mean biases for the improved and current AERMOD methods have approximately equal magnitudes, although the current method slightly underpredicts u* while the new method slightly overpredicts (by about 20 % on average).

The geometric means of the predicted to observed ratios of u* for low wind speeds are also tabulated in Table 6-1. These are the same numbers indicated as the 50^{th} percentile in Figure 6-7 and discussed above.

Figure 6-7: Box and Whisker Plots of u* Predicted / Observed for Low Wind Speeds (<3.0 m/s[-1])

Plots are provided for single-level AERMET, modified single-level, two-level AERMET, hybrid Luhar two-level and unmodified Luhar two-level for (a) Cardington; (b) Bull Run; and (c) FLOSS II. Each box represents 25-75 percentiles and whiskers extend to 10 and 90 percentiles.

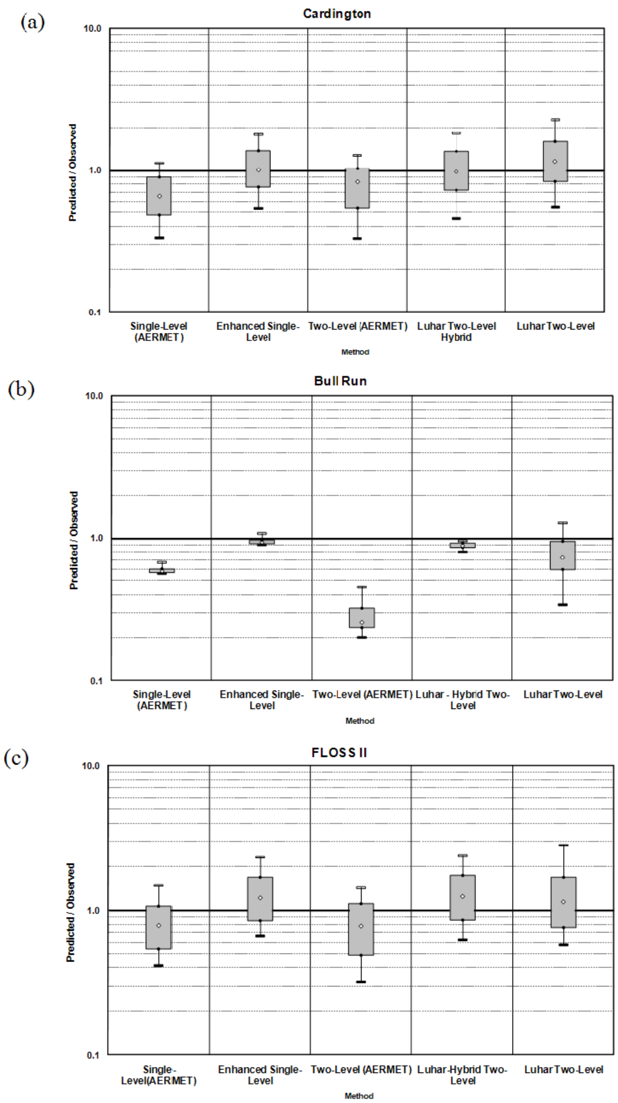


Table 6-1: Calculated Bias (Geometric Mean of the Ratio of Predicted to Observed) for Derived Frictional Velocity for Observed Wind Speeds of < 3.0 m/s^{-1}

u_*, Cardington				
AERMET Single-Level	**Enhanced Single-Level**	**AERMET Two-Level**	**Luhar Two-Level**	**Hybrid Luhar Two-Level**
0.63	**0.99**	**0.70**	**1.09**	**0.94**
u_*, Bull Run				
AERMET Single-Level	**Enhanced Single-Level**	**AERMET Two-Level**	**Luhar Two-Level**	**Hybrid Luhar Two-Level**
0.61	**0.98**	**0.28**	**0.70**	**0.91**
u_*, FLOSS II				
AERMET Single-Level	**Enhanced Single-Level**	**AERMET Two-Level**	**Luhar Two-Level**	**Hybrid Luhar Two-Level**
0.77	**1.22**	**0.71**	**1.20**	**1.19**

Summary

In an initial phase of a low-wind speed evaluation study, we have conducted an evaluation of the prediction by AERMET of a key scaling parameter, u_*. For three diverse field study settings (over a large range of roughness lengths and seasons), observations from fast-response instruments were used to calculate u_*. We have tested the default AERMET formulations for single-level and two-level approaches, as well as alternative methods for each.

The results of the evaluation indicate that the alternative methods have better performance for u_* (except possibly for FLOSS II, where we show roughly equivalent performance). The results are encouraging to the extent that both the default and the alternative methods were carried forth in the subsequent tracer concentration evaluation testing phase of this project, as described in the following section.

7.0 Candidate Low Wind Speed TRACER Evaluation Databases

The search for candidate field programs with suitable tracer databases for use in this model evaluation exercise targeted those field programs involving low-wind speed meteorological conditions. Emissions near ground level were preferable. Other factors considered were the release type, dispersion environment, robustness of the sampling network, available meteorological data, and condition of the database. These criteria are discussed below for each individual candidate database. In consultation with the project team and other dispersion modeling experts, the following list of candidate field programs and databases was created:

1. Bull Run Power Plant[7]
2. Three Mile Island Atmospheric Diffusion Study[12]
3. Air Resource Laboratory (ARL) - Diffusion Under Low Wind Speed Conditions Near Oak Ridge, TN[13]
4. ARL - Diffusion Under Low Wind Speed Inversion Conditions (near Idaho National Engineering Laboratory)[14]
5. Stagnation Model Evaluation Program (STAGMAP)[15]
6. India Institute of Technology (IIT), Delhi[16,17]

We considered recommendations made by the project sponsors, by the USEPA, and by other stakeholder groups in our choice of three databases for the dispersion model evaluations.

Of the six candidate databases listed above, we obtained reports and other details for each except the last one (IIT). Summary information about these studies is provided in Table 7-1, and further information for each study is provided below.

Table 7-1: Summary of Six Candidate Low Wind Speed Tracer Field Studies

Study: Bull Run			
Release Type:	Elevated 244-meter stack at a coal-fired power plant, continuous buoyant release, no downwash, SF_6 injected into stack plume		
Dispersion Environment:	Full range of atmospheric stabilities, rolling terrain		
Time Study Conducted:	Summer/Fall 1982 Phase 1: 07/28 - 08/24 19 days of experiments Each experiment ~12-13 hours in duration Release times occurred during daytime hours and during transitional hours near sunrise/sunset	Phase 2: 09/22 - 10/18 19 days of experiments Each experiment ~12-13 hours in duration	
Sampling Network:	0.5 km arc every 8° 1.0 km arc every 8° 2.0 km arc every 4° 5.0 km arc every 4° Additional placed on nearby terrain	7.0 km arc every 2° 10.0 km arc every 2° 15.0 km arc every 2° 20.0 km arc every 2°	30.0 km arc every 2° 40.0 km arc every 2° 50.0 km arc every 4°
Meteorological Data:	122-Meter Tower Ws, Wd, and Temp at 10,30,50,100,122 meters DeltaT at 10-50, 10-100, 30-122 meters Dewpoint at 100 meters 10-meter wind speed varies from 0.3 - 2.99 m/s	10-Meter Tower Temp at 2, 10 meters DeltaT at 2-10 meters	Central Station Atmospheric Pressure Visibility Cloud Cover Dewpoint Precipitation Surface Temp Net, solar, sky radiation Vertical Sounding (Temps, Winds)
Condition of Database:	Database is well documented and organized. It is available in an electronic format.		
Pros/Cons:	Pros: - - low-wind speed observations under stable and unstable conditions	Cons: • none • only elevated buoyant release • plume stayed aloft at night	

Table 7-1: Summary of Six Candidate Low Wind Speed Tracer Field Studies (continued)

Study: Three Mile Island			
Release Type:	Phase 1: Open-field; no downwash, non-buoyant, continuous release Release height for all experiments was ~ 1 meter	Phase 2: Release near containment vessel, with downwash, non-buoyant, continuous release	
Dispersion Environment:	Flat terrain with mountains in distance, stable inversion conditions		
Time Study Conducted:	Summer/Fall 1971 Phase 1: 08/25 - 09/24 5 days of experiments Each experiment ~ 45 min release Release times occurred during early morning prior to sunrise	Phase 2: 10/06 - 10/16 5 days of experiments Each experiment ~ 45 min release	
Sampling Network:	Phase 1: Test 2: 94-190 meters downwind every 20° Test 3-6: 94-101 meters downwind every 20°	Phase 2: Tests 7-11: 149-259 meters downwind at 20 degree intervals	
Meteorological Data:	30-Foot Tower (South Field) Ws, Wd, sigma theta Range of wind speed: 0.15 - 1.50 m/s	100-Foot Tower (North) Ws, Wd, sigma theta, temp, RH, DeltaT (25-100ft) Range of wind speed: 0.58 - 1.65 m/s	100-Foot Tower (South) Ws, Wd, sigma theta Range of wind speed: 0.15 - 1.80 m/s
Condition of Database:	Database is well organized however the data is all in paper copy. We are not aware of an electronic format of this database. It would take considerable work to fully digitize all the sampling data.		
Pros/Cons:	Pros: • database is well organized • low-wind speed observations under stable conditions	Cons: • data is not in electronic format	

Table 7-1: Summary of Six Candidate Low Wind Speed Tracer Field Studies (continued)

Study: Oak Ridge Tennessee			
Release Type:	Open-area, no downwash, non-buoyant, continuous release Release height for all experiments was ~1 meter		
Dispersion Environment:	Rolling terrain (forest on outskirts of sampling area), stable inversion conditions		
Time Study Conducted:	Summer 1974 07/29 – 08/13 11 days of experiments Each experiment 1 hour release Release times occurred during mainly early to mid morning after sunrise		
Sampling Network:	Sampling occurred in heavily forested area; 100 meter arc every 6°; 200 meter arc every 6°; 400 meter partial arc every 6°; Additional samplers placed near road and river edge		
Meteorological Data:	30.5-meter towers (4) around sampling areas Ws at 2, 30 meters Range of wind speed: 0.15 - 0.75 m/s	30.5-meter tower (near release point) Ws, Wd at 2, 4, 8, 16, 30.5 meters	South TVA Tower Temp at 23, 61 meters
Condition of Database:	Database is well organized however the data is all in paper copy. We were not aware of an electronic format of this database. ΔT temperature data also does not appear in documentation. Only resultant stability class derived from the ΔT. It took considerable work to digitize the sampling data.		
Pros/Cons:	Pros: • Database is well organized- low-wind speed observations under stable conditions- wind speeds are extremely low.	Cons:- • Data was not in electronic format - meteorological measurements not as robust as other field programs- tracer release occurred in a cleared area of a dense forest with observing network located in adjacent field.	

Table 7-1: Summary of Six Candidate Low Wind Speed Tracer Field Studies (continued)

Study: Idaho Falls		
Release Type:	Open-area, no downwash, non-buoyant, continuous release Release height for all experiments was ~1.5 meter	
Dispersion Environment:	Flat even terrain, stable inversion conditions	
Time Study Conducted:	Winter/Spring 1974 02/07 - 05/22 11 days of experiments Each experiment 1 hour release Release times occurred during very early morning before sunrise	
Sampling Network:	Sampling occurred in open plain 100 meter arc at 6 ° intervals 200 meter arc at 6 ° intervals 400 meter arc at 6 ° intervals	
Meteorological Data:	61-meter tower (located on 200-meter arc) Ws, Wd at 2, 4, 8, 16, 32, 61 meters Temp at 1, 2, 4, 8, 16, 32, 61 meters sigma theta at 4 meters DeltaT at 8-32 meters Range of wind speed: 0.75 - 1.92 m/s	
Condition of Database:	Database is well organized however the data is all in paper copy. We were not aware of an electronic format of this database. It took considerable work to digitize the sampling data.	
Pros/Cons:	Pros: - Database is well organized - Low-wind speed observations under stable conditions	Cons: • Data were not in electronic format.

Study: STAGMAP	
Release Type:	Release height for all experiments was ~7 meters 2 different release points: • One was located within the densest commercial / residential area of Medford; • The second release site was on the edge of the industrial area
Dispersion Environment:	Deep pooling valley
Time Study Conducted:	Winter 1991 01/01 - 02/1036 days of experiments; Each experiment 1 hour release except experiment 14 which was a 12.5 hour release and experiment 23 which was a 2 hour release Release times occurred during very early morning before sunrise
Sampling Network:	23 sampling location located throughout Medford, OR area Samplers located anywhere from <100 meters to 4-km away depending on the location of the release

Table 7-1: Summary of Six Candidate Low Wind Speed Tracer Field Studies (continued)

Meteorological Data:	30-meter tower (Bullock Road): *SODAR (15-min averages):* Ws, Wd, sigma theta, vertical Ws, sigma of vertical Ws, inversion height / mixing depth *10 and 30-meter level (15-min averages)* Prop vane - Ws, Wd sigma theta, temp*6 and 21-meter level (15-min averages):* Sonic - Ws, sigma Ws, vertical Ws, sigma vertical Ws, sigma Temp Prop vane - Ws, sigma Ws, Wd, sigma theta (temp, RH) *2-meter level (15-min averages):*Temp	10-meter tower (Armory Rd and Hamilton St): *10-meter level (15-min averages):* Prop vane - Ws, Wd sigma theta, deltaT(10-2) *2-meter level (15-min averages):* temp, RH, pressure, RH, solar radiation	10-meter tower (Howard Ave): *10-meter level (15-min averages):* Ws, Wd sigma theta
	Armory Road 10-meter wind speed range 0.10 - 12.71 m/s		
Condition of Database:	Database is well organized and data is available in electronic format.Sampler UTM coordinates are referenced but appear not to be available in documentation we have.		
Pros/Cons:	Pros:- • Low-wind speed observations under stable and unstable conditions- extensive meteorological measurements field programs- database already used for CALPUFF evaluation which could minimize model setup work	Cons: • Sampler UTM coordinates are referenced, but appear not to be available in documentation we have • Samplers are not in a regular array and are too sparse.	
Study: India Institute of Technology, Delhi			
Release Type:	Urban city, no downwash, non-buoyant, continuous release height for all experiments was ~1 meter and occurred in a sports arena nearly surrounded on all sides		
Dispersion Environment:	Flat terrain, stable and convective conditions		
Time Study Conducted:	February 1991 2/13 - 2/21 Day 1: release occurred all day with 5 different 30-minute sampling times Day 2,3: 9 60-minute releases followed by sampling conducted during the second 30-minutes of each release		
Sampling Network:	Sampling occurred in open area 500 meter arc at 45 ° intervals 100 meter arc at 45 ° intervals 150 meter arc at 45 ° intervals 200 meter arc at 45 ° intervals (sometimes)		
Meteorological Data:	30-meter tower Ws, Wd, Temp at 1, 2, 4, 8, 15, 30 meters Range of wind speed: 0.29 - 1.56 m/s @ 15 meters		
Condition of Database:	Currently do not have full documentation on this database, although it seems like a promising one to possibly include later. It has some releases under low-wind speed conditions for various stability classes.		
Pros/Cons:	Pros: •	Cons: •	

7.1 Bull Run

The Bull Run field program was conducted as part of the Electric Power Research Institute's (EPRI) PMV&D project in 1982. The field program was designed to gather concurrent tracer release characteristics along with meteorological and sampling data. This database was used in evaluating and improving existing atmospheric dispersion models primarily used for tall stack releases, such as those associated with electric generating facilities.

The field program took at the Bull Run Generating Station (BRGS) near Oak Ridge, Tennessee during the summer/fall of 1982. The field program consisted of two phases. Phase 1 started on July 28th and ended on August 24th. During this period, 19 days of experiments were conducted with each experiment lasting approximately 12-13 hours. Phase 2 started on September 22nd and ended on October 18th. During this period, 19 days of experiments were conducted with each experiment lasting approximately 12-13 hours.

The SF_6 tracer release occurred from an elevated (244-meter) stack located at the BRGS. Tracer was injected directly into the stack plume (i.e., a buoyant elevated release). The height of the stack is sufficiently greater than the nearby obstacles that the plume is not subject to building downwash. Terrain surrounding the tracer release point is classified as rolling terrain. The SF_6 releases for all experiments were continuous in nature and occurred during daytime and transitional hours near sunrise/sunset. The various release times were designed to occur under a full range of atmospheric stabilities, but the time periods of the experiment were mostly during the daytime.

The sampling grid used to measure the tracer gas concentrations was located on the arcs referenced in Table 7-2.

Table 7-2: Bull Run Sampling Grid

Downwind Distance	Arc Spacing	Downwind Distance	Arc Spacing
0.5 km	8°	15.0 km	2°
1.0 km	8°	20.0 km	2°
2.0 km	4°	30.0 km	2°
5.0 km	4°	40.0 km	2°
7.0 km	2°	50.0 km	4°
10.0 km	2°		

Note: Additional samplers were placed on nearby terrain.

Also, see Figure 9-3 for the sampler graphical depiction.

Not all sampling arcs were used for all experiments. If stable conditions were expected, the farthest arcs (past 2 km) were used. If unstable conditions were expected, the closest arcs were used (closer than about 20 km).

The meteorological measurements during the field program occurred at three locations:

1. a 122-meter tower which observed:
   a. Wind speed, wind direction, and temperature at 10, 30, 50, 100, and 122 meters
   b. Delta-T at 10-50, 10-100, and 30-122 meters
   c. Dew point at 100 meters

2. a 10-meter tower which observed:
   a. Temp at 2, 10 meters
   b. Delta-T at 2-10 meters

3. a Central Station which observed:
   a. Atmospheric pressure
   b. Visibility
   c. Cloud cover
   d. Dew point
   e. Precipitation
   f. Surface temperature
   g. Net and solar radiation
   h. Vertical Sounding (temperatures, winds)

The 10-meter wind speed observations from the 122-meter tower vary from 0.3 to 2.99 m/s.

The Bull Run database is well documented and organized. It is available in an electronic format. It is the only elevated buoyant release of the databases that were considered and has low-wind speed observations under a few stable hours, with most during unstable conditions. The evaluation documented in this report used both stable and unstable hours.

7.2 Three Mile Island Atmospheric Diffusion Study

The Three Mile Island Atmospheric Diffusion Study was conducted to further study the plume meander due to wind direction fluctuations during low-wind speed conditions at the Three Mile Island Nuclear Station. It was important to know if the observed wind direction meander under low wind speed conditions was actually occurring or if it was an inaccuracy due to characteristics of the wind vane. Low wind speeds had been often observed by the meteorological instruments at Three Mile Island for several years prior to the study.

The Three Mile Island Atmospheric Diffusion Study was conducted during the summer and fall of 1971 and consisted of two phases. Phase 1 was an open-field non-buoyant, continuous release with no downwash and occurred starting on August 25th and ending on September 25th. During this period, 5 days of experiments were conducted with each experiment consisting of a 45-minute release concurrent with at least 45 minutes of sampling. The Phase 2 release occurred near the containment vessel and was a non-buoyant, continuous release subject to building downwash. The releases occurred starting on October 6th and ending on October 16th. During this period, 5 days of experiments were conducted with each experiment consisting of a 45-minute release concurrent with at least 45-minutes of sampling.

The SF_6 tracer release occurred at 1 meter above grade for all experiments. The Phase 1 open field release was situated far enough from any structures that would cause the plume to experience building induced downwash. Conversely, the Phase 2 release, near the containment vessel, was possibly affected by with building downwash from nearby structures. However it is unclear whether the downwash conditions are effective for near-calm conditions. The terrain surrounding each of the tracer release points is relatively flat. The SF_6 releases for all experiments were continuous in nature and occurred during early morning stable inversion conditions just prior to sunrise.

The sampling grid used to measure the tracer gas concentrations was located on the arcs listed in Table 7-3.

Table 7-3: Three Mile Island Atmospheric Diffusion Study Sampling Grid

Experiment	Downwind Distance	Arc Spacing
Test 2	94-190 m	20°
Test 3	94-101 m	20°
Test 7-11	149-259 m	20°

The meteorological data measurements during the field program occurred at three locations:

1. 30-foot south field tower observed wind speed, wind direction, sigma theta at 30 ft (9 m)

2. 100-foot north tower observed wind speed, wind direction, sigma theta, temperature, relative humidity, and delta-T (23-100 ft) at 100 ft (30 m)

3. 100-foot south tower observed wind speed, wind direction, sigma theta at 100 ft (30 m)

The wind speed observations from the 100-foot south tower varied from 0.15 to 1.80 m/s. Similar ranges in wind speed occurred at the other towers.

The Three Mile Island database is well documented and organized. The database has very low wind speed observations under stable conditions. At the current time, the data is all in paper copy and we are not aware of an electronic format of this database.

This experiment and the two following experiments were used by VanderHoven[18] to develop dispersion curves for light wind stable conditions, for use in NRC models.

7.3 ARL - Diffusion under Low Wind Speed Conditions (Oak Ridge, TN)

The ARL's "Diffusion Under Low Wind Speed Conditions (Oak Ridge, Tennessee)" field program was conducted to obtain field data of diffusion in rough terrain under conditions of light wind speeds and stable lapse rates. The field program was sited along the Clinch River approximately 16 miles south of downtown Oak Ridge, Tennessee. This field program was one in a series designed to gather data suitable for model evaluation during atmospheric conditions that are the most limiting in terms of the highest predicted ground-level concentrations.

This field program was conducted during the summer of 1974. The field program consisted of a continuous release (non-buoyant) in an open area with no downwash. The experiment started on July 29th and ended on August 23rd. During this period, 11 days of experiments were conducted with each experiment consisting of a 1-hour release followed by continuous sampling.

The tracer gases released for this field program were SF_6 and Freon ($12B_2$). The releases occurred 1 meter above the ground for most experiments, except for experiments 10 and 11 when SF6 was released at a point 30.5 meters above the ground. The releases occurred in an open area with gentle terrain slopes surrounded by a heavily wooded forest. The releases for all experiments occurred during mainly early (before sunrise) to mid morning after sunrise, comprising a mix of stable and unstable conditions.

The sampling grid used to measure the tracer gas concentrations was located on the arcs referenced in Table 7-4.

Table 7-4: Oak Ridge Sampling Grid

Downwind Distance	Arc Spacing
100 m	6°
200 m	6°
400 m	6°

Note: Additional samplers were placed near the road and river's edge.

Also, see Figure 9-5 for the sampler graphical depiction.

The meteorological data measurements during the field program occurred at 6 locations:

1. Four 30.5-meter towers bracketing the sampling grid - observed wind speed at 2, 30 meters;

2. a 30.5-meter tower located near release point - observed wind speed and wind direction at 2, 4, 8, 16, 30.5 meters; and

3. a South TVA Tower observed temperature at 23 and 61 meters.

The wind speed observations from the 30.5-meter tower located near the release point vary from 0.15 to 0.75 m/s.

We have found, however, that the winds were so light during the field experiments that the only reliable wind speeds are available through special laser anemometers. These wind speeds are consistent with those used by Hanna et al.[19].

7.4 ARL - Diffusion under Low Wind Speed Inversion Conditions (Idaho Falls)

The ARL's "Diffusion Under Low Wind Speed Inversion Conditions" field program (referred to as the "Idaho Falls field program") was conducted to obtain field data of diffusion in flat, even terrain under conditions of light wind speed and stable lapse rates. The field site was a field near the Idaho National Engineering Laboratory (INEL) in southeastern Idaho. This was one of several field programs designed to gather data suitable for model evaluation for atmospheric conditions associated with high ground-level concentrations (VanderHoven[18]).

The Idaho Falls field program was conducted during the winter/spring of 1974. The continuous release was non-buoyant and no buildings were nearby. Releases started on February 7th and ended on May 22nd. During this period, 11 days of experiments were conducted with each experiment consisting of a 1-hour release and concurrent continuous sampling.

The tracer gas released for this field program was SF_6. The releases occurred 1.5 meters above grade for all experiments. The releases occurred in an open plain at an elevation of approximately 1500 meters above mean sea level. The releases for all experiments occurred during mainly early morning hours when stable inversion conditions were most prevalent.

The sampling grid used to measure the tracer gas concentrations was located on the arcs referenced in Table 7-5.

Table 7-5: Idaho Falls Field Program Sampling Grid

Downwind Distance	Arc Spacing
100 m	6°
200 m	6°
400 m	6°

Also, see Figure 9-4 for the sampler graphical depiction.

The meteorological measurements were taken at one location. A 61-meter tower was located on the 200 meter arc and observed wind speed and wind direction at 2, 4, 8, 16, 32, 61 meters and temperature at 1, 2, 4, 8, 16, 32, 61 meters. Delta-T was also calculated from the 8-32 meter levels.

The wind speed observations from the 61-meter tower located on the 200-meter arc vary from 0.75 to 1.92 m/s.

The Idaho Falls database is well documented and organized. The database has very low wind speed observations under stable conditions.

7.5 STAGMAP

The Stagnation Model Evaluation Program (STAGMAP) in Medford, OR, had several objectives. Of interest to our study, concurrent meteorological data and monitoring data were collected in order to study dispersion under low-wind speed stagnation condition within a deep pooling valley.

STAGMAP was conducted during the winter of 1991. The continuous release was nonbuoyant and was not subject to downwash. The experiment started on January 1st and ended on February 10th. During this period, 36 days of experiments were conducted with each consisting of a 1-hour release concurrent with continuous sampling, except for experiment 14, which was a 12.5 hour release and experiment 23, which was a 2 hour release.

The tracer gases released for this field program were SF_6 and Freon ($13B_1$). Tracer releases were made 6 hours apart alternating between the two tracer gases. The releases occurred 7 meters above grade for all experiments to approximate a rooftop release on a typical residence in Medford. The experiment had two alternate release sites. One was located within the densest commercial / residential area of Medford, while the second release site was on the edge of the industrial area. The releases for all experiments occurred mainly during very early morning before sunrise.

The sampling grid for this project was not set out on arcs, due to obstacles in the urban setting. There were a total of 23 samplers located throughout the Medford area at distances ranging from about 100 meters to about 4 km away, depending on the location of the release.

There was much meteorological data recorded during STAGMAP. Table 7-6 summarizes this data. The wind speed observations from the Armory Road 10-meter tower range from 0.10 to 12.71 m/s.

Table 7-6: Meteorological Data Recorded during STAGMAP

30-meter tower (Bullock Road)	10-meter tower (Armory Rd / Hamilton St)	10-meter tower (Howard Ave / White City)
SODAR (15-min averages):Ws, Wd, sigma theta, vertical Ws, sigma of vertical Ws, inversion height / mixing depth 10 and 30-meter level (15-min averages): Prop vane - Ws, Wd sigma theta, temp 6 and 21-meter level (15-min averages): Sonic - Ws, sigma Ws, vertical Ws, sigma vertical Ws, sigma Temp; Prop vane - Ws, sigma Ws, Wd, sigma theta (temp, RH) 2-meter level (15-min averages): Temp	10-meter level (15-min averages): Prop vane - Ws, Wd sigma theta, delta-T(10-2) 2-meter level (15-min averages): temp, RH, pressure, RH, solar radiation	10-meter level (15-min averages): Ws, Wd sigma theta

The STAGMAP database is well documented and organized. The database has very low wind speed observations under stable and unstable conditions. In addition, the data is available in electronic format. The database contains an extensive meteorological measurements field programs.

During the early evaluation phase of our work, we started to consider the possibility that the STAGMAP tracer releases may have resulted in a slumping (heavier than air) plume. The experiment documentation indicates that the SF_6 was released in large quantities (about 10 g/s) in an undiluted form. Since SF_6 is has a molecular weight of 146 vs. 29 for dry air, it could have behaved like a heavy dense gas in calm atmospheric conditions. This possibility was suggested after we conducted some sensitivity modeling using SLAB[20], a dense gas model. SLAB predicted that under light wind stable conditions (conditions upon which the study was focused) the plume would drop from the release height of 7 meters to the ground within a few meters. This possible complication, which needs additional investigation, caused us to set aside the use of STAGMAP as one of the database selected for the tracer evaluation at this time.

8.0 Selection of Databases for AERMOD Tracer Evaluation

Three of the databases described above were selected for the current tracer evaluation portion of the AERMOD low wind speed study. Those databases are: (1) Bull Run, (2) Idaho Falls, and (3) Oak Ridge. These three databases were selected because they are high quality research grade experiments designed to evaluate atmospheric dispersion under low wind speed conditions. The remaining databases are available for future independent evaluations, as is half of the Bull Run database, which was reserved for future independent evaluations.

9.0 AERMOD Modeling Procedures and Input Data

This section describes the procedures by which the data for each field program were modeled and also describes the data selection process and how the data from each field program were entered as input into AERMOD. The modeling procedures for each field program are discussed in separate subsections below. There is a subsection dedicated to each of the following areas: (1) AERMOD model configurations, (2) meteorological data development, (3) description of release point and source modeling parameters, (4) description of sampler arrays, and (5) review and compilation of tracer observation data.

9.1 AERMOD Model Configurations

AERMOD (Version 07026) and AERMET (Version 06341) were used with USEPA default settings and recommendations to evaluate the model's performance versus observed concentrations. In addition, two model enhancements designed to improve the model predictions in light wind speed conditions were considered. The three model configurations that were tested are referred to as:

(1) **Base Model** → Current AERMET and AERMOD

(2) **Modified AERMET** → new AERMET (with updated u_* formulation described in Part 1 of this report (Paine et al.20) and current AERMOD

(3) **Higher Minimum Sigma-v** → new AERMET (with update u_* formulation and new AERMOD versions with minimum sigma-v increased from 0.2 to 0.4.

The evaluation used the three databases to investigate stable light wind speed conditions. Both the Idaho Falls and Oak Ridge experiments were low-level releases under mostly stable light wind speed conditions. Bull Run consisted of a buoyant elevated release under light wind speed conditions, but mostly under unstable conditions. To the extent possible, the modeling was conducted with the most recent prescribed methods by USEPA and those methods outlined in the AERMOD User's Guide and the AERMOD Implementation Guide (AIG) as would be required in a regulatory setting.

Each of the three evaluation databases was run to determine a base set of modeling results using AERMET/AERMOD as currently provided by EPA (the Base Model referred to above). Since the model enhancements emphasize revisions during light wind stable conditions, the two modified versions of AERMET/AERMOD mentioned above were only evaluated for Idaho Falls and Oak Ridge. Each set of model predictions was compared with each other and with the measured tracer concentrations to determine the current AERMET/AERMOD level of performance and the performance of the modified AERMET/AERMOD versions.

For each model configuration, building downwash effects were not considered because the Idaho Falls and Oak Ridge experiments occurred in open fields and the Bull Run stack is taller than the Good Engineering Practice (GEP) formula height. Terrain effects were not considered for Idaho Falls due to the relative flat nature of the release location, however terrain was considered for Bull Run and initially for Oak Ridge as well. Ultimately, we found that the consideration of rolling terrain for Oak Ridge had a small effect upon results. Due to the gentle nature of the terrain, we followed the AIG recommendations to consider flat terrain in such situations. This simplifies model debugging, too. We also assumed relatively flat terrain for the Oak Ridge experiment. For those instances when terrain was considered, AERMAP (version 09040) was run to estimate each modeled receptor location's (which corresponded to sampler bag locations) terrain elevation and critical hill height. AERMAP was run using default settings along with terrain data extracted from the United States Geological Survey (USGS) National Elevation Data (NED) 30-meter resolution dataset. Receptor flagpole heights were also accounted for and set to the elevation above the ground for each sampler. Receptor flagpole heights were entered as 0.76 meters for Idaho Falls and Oak Ridge and approximated at 2.0 meters for Bull Run.

9.2 Meteorological Data Preparation for Analysis

AERMET (Version 06341) is AERMOD's meteorological preprocessor. For the model evaluation based on three alternate AERMOD formulations, three sets of model-ready meteorological data were required. AERMET was first run using the current version of the model and then a second time using the modified version of AERMET that accounts for an adjusted u_* formulation. The third version of AERMET considered the adjusted u_* formulation and a new minimum sigma-v of 0.4. All three AERMET runs used identical inputs, with the difference consisting only of a different executable file in the adjusted u_* and new minimum sigma-v cases.

For each experiment, AERMET was run using meteorology observed as part of each field program as the primary source of observations. For all databases, at least one level of winds was available. For Oak Ridge and Bull Run, the modeled wind direction was determined based on the direction where the highest monitored concentration was recorded in the sampling grid. For Idaho Falls, the actual observed wind direction was used because the sampling grid completely surrounded the release point in all possible directions. With the flat terrain, the arc maximum was independent of the selection of the wind direction.

For other meteorological variables needed for the modeling, but not available from the on-site instrumentation (such as pressure, dew point, and cloud cover), data values were taken from a nearby NWS airport. Data from the following airports were used to supplement the on-site data:

(1) Idaho Falls - Idaho Falls Fanning Field: pressure, temp, dew point, and cloud cover

(2) Oak Ridge - Knoxville Mcghee Airport: pressure, temp, dew point, and cloud cover

(3) Bull Run - no supplemental airport data was needed.

A detailed listing of available meteorological data for each database is provided in Table 7-1. Please note that not all the data listed in Table 7-1 were used in the evaluation study.

The land use characterization surrounding the meteorological measurement site was a major concern. There is a difference in how AERMET was applied to create the AERMOD-ready surface and profile files for each database. For Bull Run, AERSURFACE, the EPA land use pre-processor tool, was used to determine the albedo and Bowen ratio (based on a 10-km area average). The surface roughness was set to be 0.51 meters (Bowne et al.[7]). For Oak Ridge, AERSURFACE was used again; however the resulting surface roughness values were not consistent with what would have been expected for this area based on visual inspection of an aerial photograph. After reviewing the aerial photograph and the 1992 National Land Cover Data (NLCD) (used as input to AERSURFACE), we found that the 1992 NLCD data mischaracterizes some of the land use surrounding the Oak Ridge release point by overstating the areal coverage of forests. Therefore, only the albedo and Bowen ratio values from the AERSURFACE runs were used (based on a 10-km area average) and the surface roughness was estimated at 0.2 m. For Idaho Falls, the database documentation indicates the area is/was mainly desert shrub land. Based on this classification, the AERSURFACE default values for the non-arid shrub land category were selected. For each database, the appropriate Bowen ratio (average, wet, or dry) was selected based on a comparison of the monthly precipitation amount relative climate normals. Figures 9-1 and 9-2 show the location of the release points and land use surrounding Bull Run and Oak Ridge, respectively. It is recognized that Figures 9-1 and 9-2 represent a much more recent depiction of the Oak Ridge experiment area. However, Figures 9-1 and 9-2 can be considered a reasonable representation of the area at the time of the experiment. This conclusion is based upon evidence found in the Oak Ridge NOAA technical document Figure 19 and from descriptions provided by Steve Hanna (in personal communications with Mr. Robert Paine). Sampler arrays for Bull Run, Oak Ridge, and Idaho Falls are shown in Figures 9-3 to 9-5.

9.3 Description of Release Point and Source Modeling Parameters

Table 9-1 summarized the details of the release parameters for all the experiments. Specific inputs of use for input to AERMOD are provided in Table 9-1 for the three field experiments chosen for modeling (Bull Run, Idaho Falls, and Oak Ridge. Note that Bull Run involved an elevated tall stack release in a buoyant plume, and Idaho Falls and Oak Ridge involved two low-level non-buoyant releases.

Table 9-1: Modeled Stack Parameters for Tracer Releases

<table>
<tr><th>Experiment</th><th>Release Height (m)</th><th>Release Temp (K)</th><th>Release Velocity (m/s)</th><th>Release Diameter (m)</th><th>Emission Rate (g/s)</th><th>Comments</th></tr>
<tr><td>Bull Run</td><td>244</td><td>400</td><td>13.5</td><td>9.0</td><td>13.0</td><td>Temp, velocity, and emission rate varied slightly on an hour to hour basis. This was accounted for in the modeling.</td></tr>
<tr><td>Idaho Falls</td><td>1.5</td><td>Ambient</td><td>0.001</td><td>0.001</td><td>0.03</td><td rowspan="2">Temp, velocity and diameter used to simulate a non-buoyant release. Emissions varied slightly hour to hour. This was accounted for in the modeling</td></tr>
<tr><td>Oak Ridge</td><td>1.0</td><td>Ambient</td><td>0.001</td><td>0.001</td><td>0.07</td></tr>
</table>

Figure 9-1: Location of Releases and Meteorological Observations for Bull Run (courtesy of Google Earth)

Note that the map is from 2009 while the experiment took place in 1982.

Figure 9-2: Location of Releases and Meteorological Observations for Oak Ridge (courtesy of Google Earth)

Note that the map is from 2009 while the experiment took place in 1974.

9.4 Description of Sampler Arrays

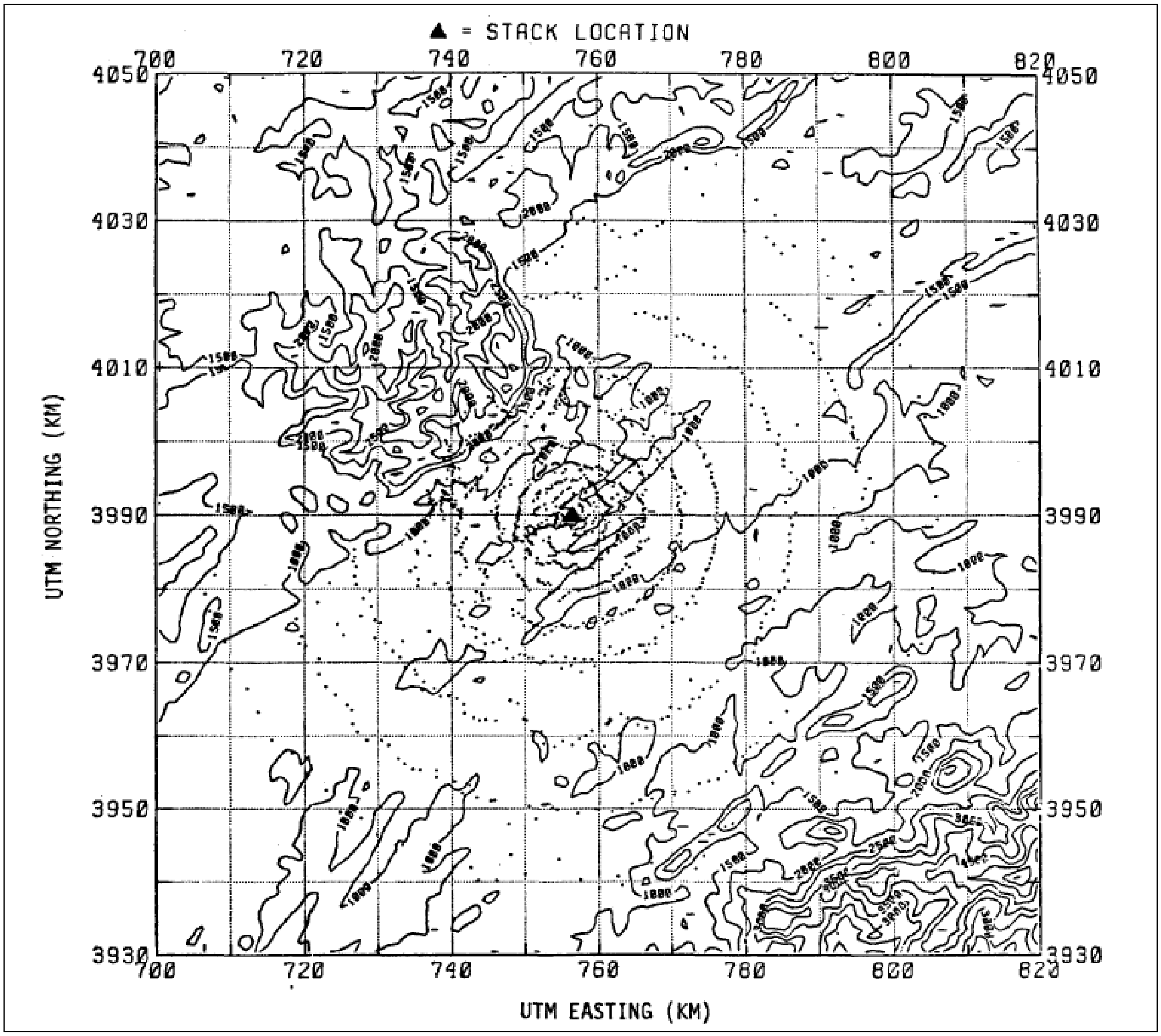
In addition to the source emissions data and meteorology data recorded during each field experiments, a dense array of samplers was deployed. The samplers were strategically located in arcs around the release point in each experiment. Sampler locations are shown in Figures 9-3 through 9-5 respectively for Bull Run, Idaho Falls and Oak Ridge. These sampler locations were used in the model evaluation.

The arcs used in the evaluation of the model correspond to the distances shown in Figures 9-3 through 9-5. For the elevated stack releases at Bull Run, the samplers ranged much further downwind, starting at 0.5 km and going as far as 50-km downwind. Specifically, receptor arcs were placed at 0.5, 1.0, 2.0, 5.0, 7.0, 10.0, 15.0, 20.0, 30.0, 40.0, and 50.0 km downwind of the source.

Table 7-2 details the varying downwind distances and sampler spacing for Bull Run. Note that not all of the samplers in the figure were used in each tracer release trial. Based on the expected wind direction and stability, only about ¼ of the samplers were used in any experiment trial.

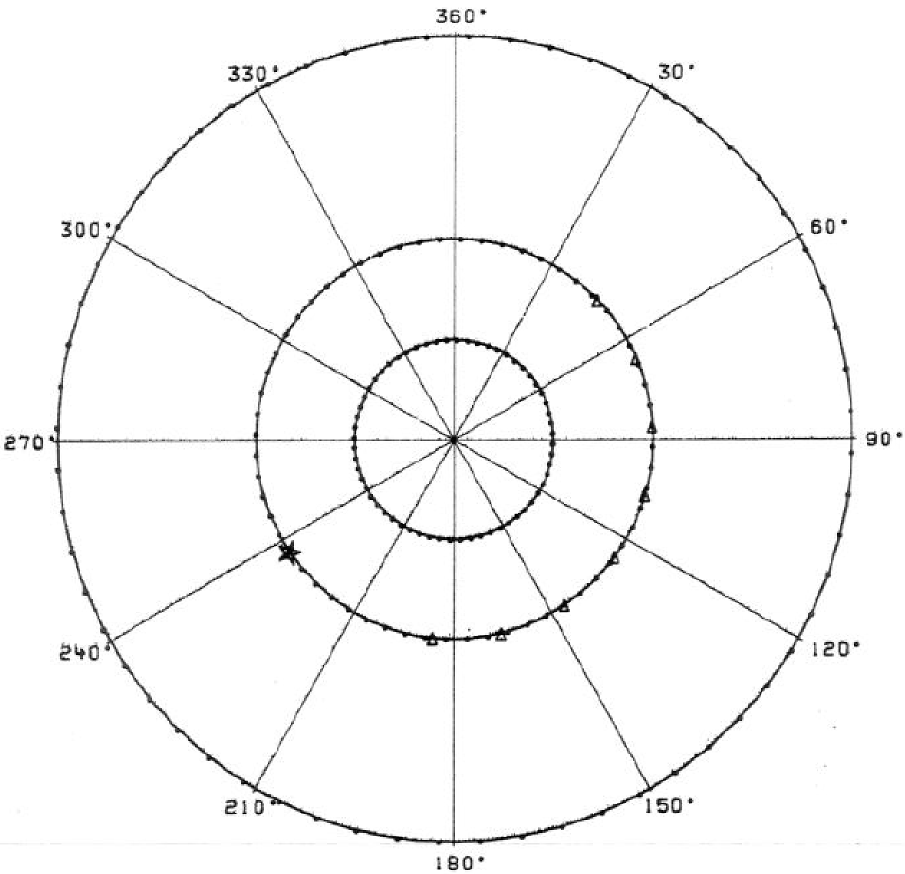
For Oak Ridge and Idaho Falls, there were arcs of samplers placed at 100, 200, and 400 meters downwind of the release point. These arcs were set up on a polar style grid and placed in concentric rings around the release point. The spacing on these arcs was 6 degrees. Tables 7-4 and 7-5 detail the sampling grid for Oak Ridge and Idaho Falls, respectively.

Figure 9-3: Depiction of Sampler Array for Bull Run



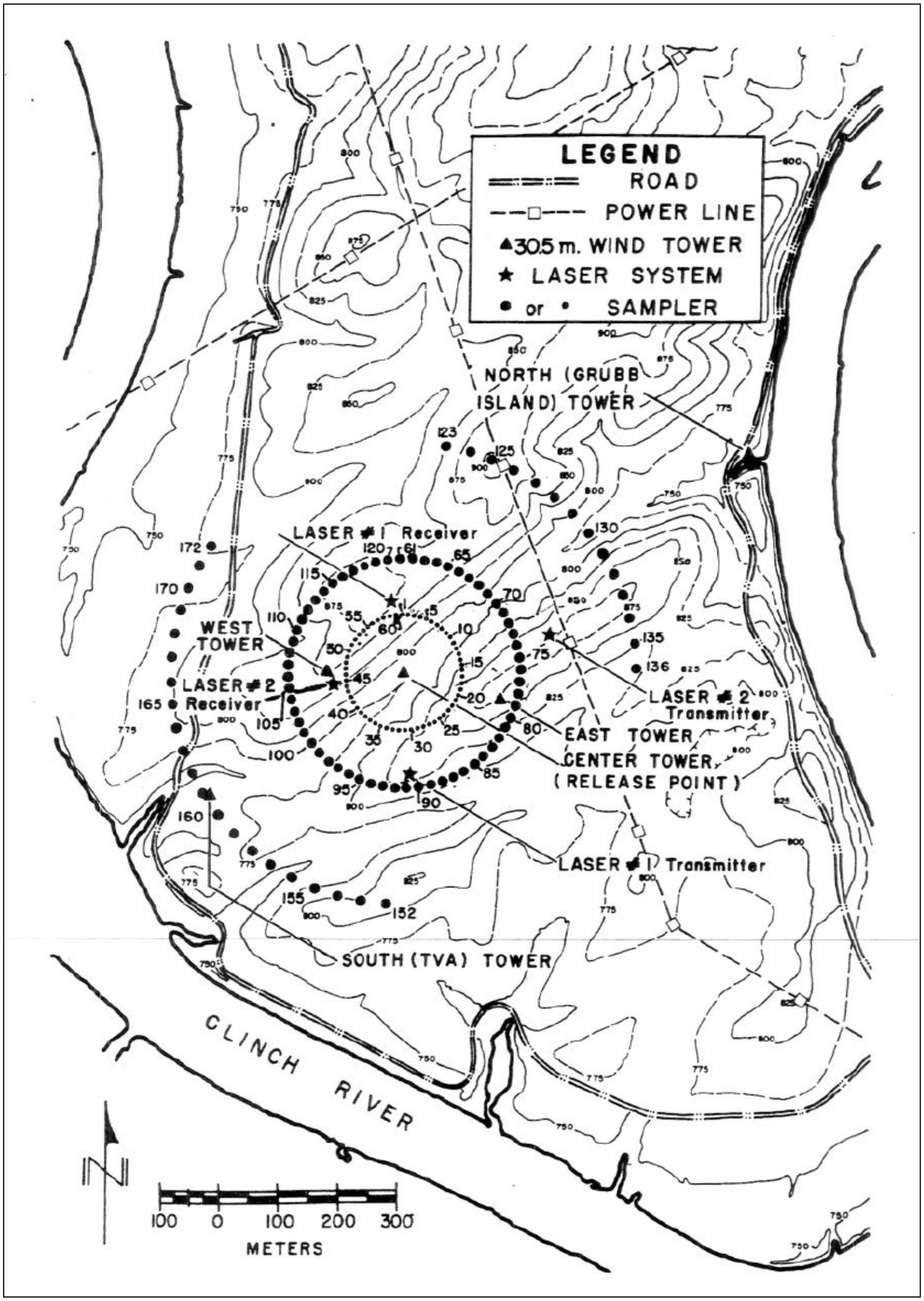
Note: For any given tracer release trial, only those sampler locations in downwind arcs covering an angle of about 100 degrees were employed. The near arcs were used only during unstable conditions and the far arcs were used only during stable conditions.

Figure 9-4: Depiction of Sampler Array for Idaho Falls



Note: the arcs are at distances of 100, 200, and 400 m from the source.

Figure 9-5: Depiction of Sampler Array for Oak Ridge



Review and Compilation of Tracer Observation data

During each experiment, an array of samplers was deployed in a manner such that the samplers were expected to intersect the centerline of the SF_6 plume. For all experiments, SF_6 concentration data values were readily available in a format suitable to be compared directly with each model's predictions.

For each hour, concentration data and/or isopleth plots of the observed SF_6 concentrations were reviewed. Isopleth (contour) plots were available for Bull Run and Idaho Falls, but were unavailable for Oak Ridge. Isopleth plots were generated for Oak Ridge and are contained with the electronic modeling files. In most instances, the isopleth plots for all the experiments provided a clear depiction on the direction for which the plume was heading for that hour. As previously stated, the wind direction in the model was set to correspond to the observed plume impact. However, in this case, the relatively flat terrain and rings of receptors made the model prediction insensitive to the actual wind direction selected for model input. These plots were also useful to determine those hours when the plume missed the arcs, so that those hours were excluded from the evaluation.

Using the raw concentration data, we calculated the arc-wide maximum observed concentration for each downwind distance represented by an arc of samplers. A fitted arc-wide maximum (as discussed below) was then used in the model evaluation.

10.0 Evaluation Procedures

The AERMOD model predictions for each selected database were compared with the measured tracer concentrations, using techniques consistent with the previous AERMOD evaluations[21]. For the candidate databases used in this evaluation study, the modeled predictions and measured concentrations were grouped on arcs of various distances. A straightforward approach was used that compared the arc-wide maximum concentrations for both modeled and measured concentrations (i.e., one pair of values per arc).

There are a number of performance measures that are widely used in dispersion model evaluation exercises, as reviewed by Chang and Hanna[22]. However, for EPA regulatory model evaluations, a subset of the available procedures is recommended. In particular, the operational performance of models for predicting compliance with air quality regulations, especially those involving a peak or near-peak values at some unspecified time and location, can be assessed with quantile-quantile (Q-Q) plots (Chambers et al.[23]). Q-Q plots were created by sorting via rank the predicted and the measured concentrations for each predetermined arc from a set of model predictions and corresponding measure concentrations that are initially paired in time and space (arc). The sorted list of predicted concentrations was then plotted by rank against the measured concentrations, also sorted by rank. These concentration pairs are no longer paired in time; however, they are still paired by downwind distance.

In addition, residual plots were utilized to analyze the model trends and bias as a function of distance. Each selected database resulted in the generation of a series of model predictions that were paired with a corresponding series of measured concentrations for various downwind distances (i.e., on each arc). The use of residual plots as a means to interpret the model performance enabled us to make a comparison among various model configurations. These plots are provided in Appendix A.

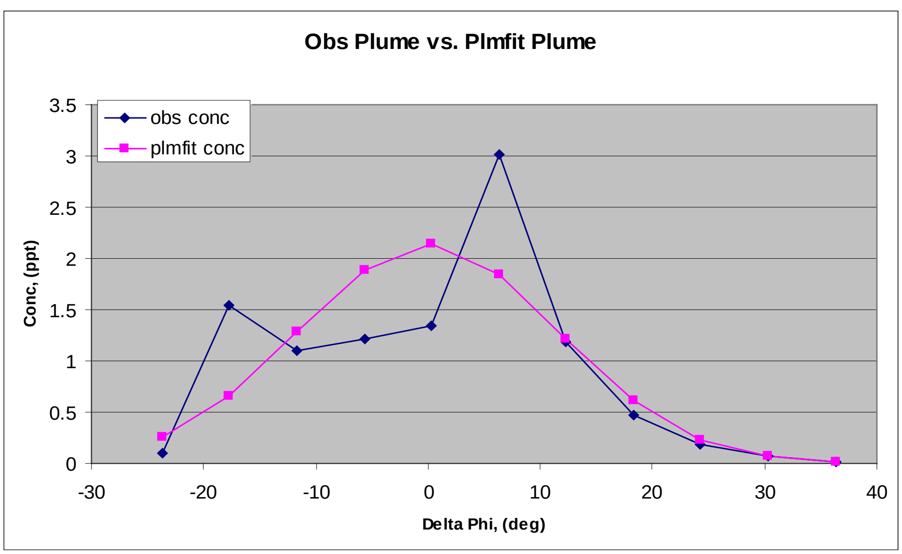
11.0 Features of a Dispersion Model with Good Performance

For this evaluation study, it is important to define what is meant by “good” model performance. Chang and Hanna[22] survey a large number of dispersion model evaluation exercises with field observations and come up with some preliminary estimates of “good” performance. For example, the relative mean bias should have a magnitude less than about 0.4, and the relative RMSE should be less than about 1. They also recommend an acceptable value for FAC2 (the fraction of cases where the predictions are within a factor of two of the observations). Their FAC2 criterion of about 50 % is the same as that in the EPA Section 9.1.2 of Appendix W). The EPA also states that, for regulatory applications, a slight overprediction bias is preferred versus an underprediction bias.

A “good” model is generally not expected to predict accurately in time and space, although this would be ideal. It is unreasonable to expect this, though, given the complex nature of the atmosphere and simplifying assumptions made in the model. Due to scales of turbulence that cannot be observed and other similar components of random uncertainty, dispersion models have limitations in accuracy for individual cases. Therefore, it is generally acknowledged that if a dispersion model can predict concentrations that are within a factor of two of the observed concentrations regardless of the direction, distance, and time when the predicted versus observed concentrations occur, then this would be considered to be acceptable performance (a “good” model). The model performance Q-Q plots shown in the next section feature factor-of-two predicted/observed ratio lines.

Another issue in this study was whether a Gaussian fit should be applied to the observed concentrations on a tracer arc to estimate the “maximum concentration”. This would be in place of the actual observed maximum concentration. An example of the irregular nature of monitored concentrations along an arc is shown in Figure 11-1, where the actual observed peak is an outlier concentration. The fitted Gaussian curve conserves the concentration sigma-y and crosswind-integrated concentration, while presenting an alternative “observed” maximum concentration that better matches the assumed smooth distribution in the model.

Figure 11-1: Example of Fitted Peak for a Tracer Arc



12.0 Results of Evaluation

The results presented here provide our findings for the AERMOD configurations noted above (current model (with parameterized sigma-theta and with observed sigma-theta), current model with AERMET improvements to u_* estimation method at low winds, and new higher minimum sigma-v in AERMET and AERMOD). The results for the three low-wind field experiment evaluation databases are provided below in the Q-Q plots. Although residual plots were also generated, these are not presented here, but are contained with the electronic modeling files. However, any important trends indicated by the residual plots are note in discussions below.

12.1 Bull Run: Tall Stack Tracer Release into Buoyant Plume

The Bull Run database is divided into developmental and evaluation portions. This initial model evaluation task is considering only the developmental portion of the database, since the evaluation portion is being reserved for final model evaluation. The peak predicted and observed concentrations at Bull Run were dominated by the unstable hours, which comprise most of the database. There is not a sufficient number of stable hours to draw a conclusion about the model performance during stable conditions. Also, it is important to note that the stable hours are generally marked by low concentrations, since the stack plume does not disperse downwards to the ground very quickly.

Figure 12-1 shows a Q-Q plot for the inner Bull Run arcs (7 km and closer) and Figure 12-2 shows a Q-Q plot for the outer arcs (beyond 7 km). As pointed out earlier, these results are dominated by the non-stable hours. The basic outcome of this evaluation is as follows:

- AERMOD under-predicts for closest and farthest arcs, but over-predicts or is unbiased at other arcs
- AERMOD does not underpredict for the arcs where the peak concentrations occur
- Except for the 500-m arc, AERMOD's performance is good in that predictions are generally well within a factor of 2 of observations.

We do not plan any further development or re-evaluation for Bull Run, due to the scarcity of significant observed concentrations during stable conditions.

Figure 12-1: Bull Run Q-Q Plot (Distances of 7 KM or less)

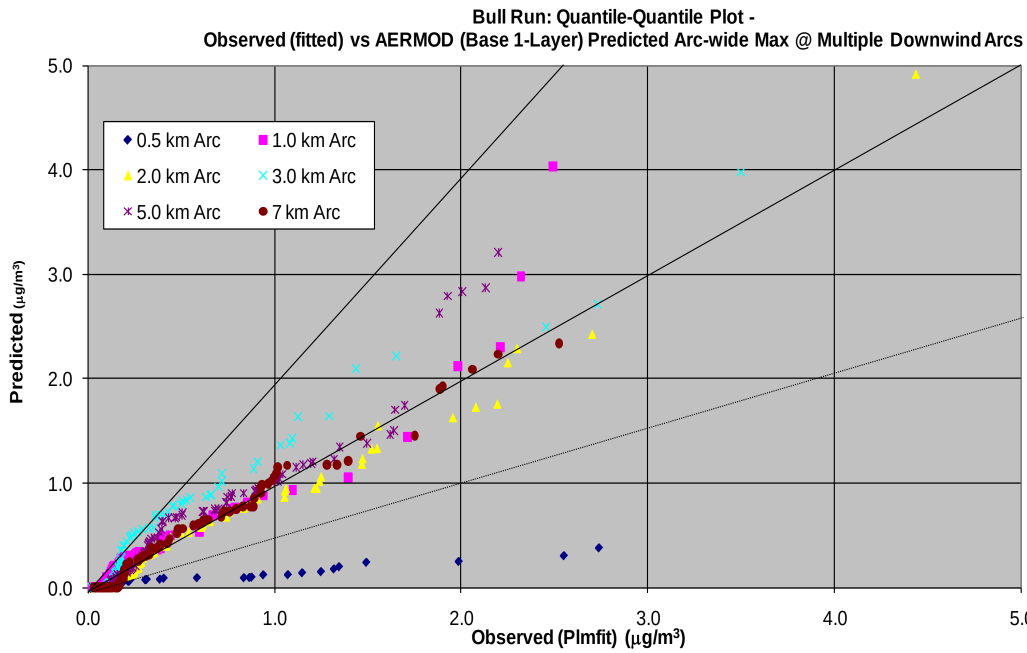
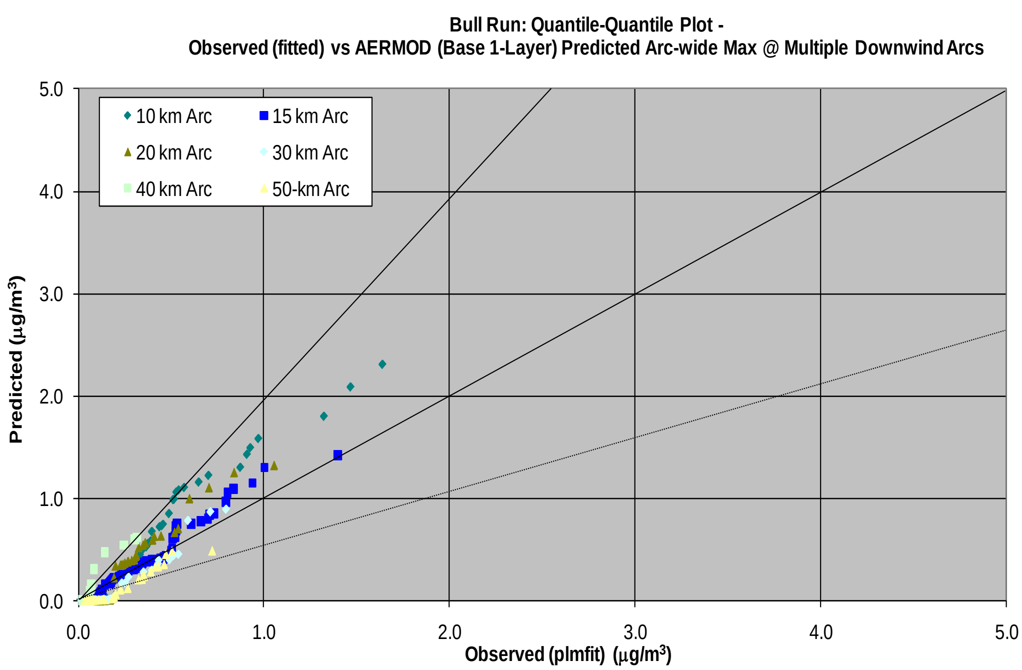


Figure 12-2: Bull Run Q-Q Plot (Distances from 10 to 50 Km)



12.2 Idaho Falls: Non-Buoyant Low-Level Tracer Release during Low Winds

The Idaho Falls tracer study provided a number of meteorological options, of which three were selected:

- the use of a single layer of meteorology with no use of sigma-theta data
- the use of a single layer of meteorology including sigma-theta data
- the use of two layers of meteorological data (with sigma-theta and delta-T data).

It is shown below that the AERMET improvements (allowing larger u_* estimates during light winds) reduced the overprediction tendency, and the inclusion of sigma-theta data further reduced the overprediction tendency. Together, these modifications greatly improved the predictions. However, there was not much difference found between the model performance with one layer or two layers of meteorological input data.

Figures 12-3 through 12-5 show Q-Q plots for the first meteorological option (single layer, no observed sigma-theta) respectively for (1) the original AERMET/AERMOD, (2) the improved AERMET u_* formulation with original AERMOD, and (3) the improved AERMET u_* formulation plus the new minimum sigma-v in AERMET/AERMOD. Figures 12-6 through 12-8 provide these same Q-Q plots in the same order for the single layer of meteorology but with observed sigma-theta included. Figures 12-9 through 12-11 contain the same types of plots for the three model versions but for the two-layer method.

Our conclusions from these Q-Q plots for Idaho Falls are as follows:

- Overpredictions are evident especially at the 100 m arc, with better model performance further out.
- Use of sigma-theta observations reduce the overpredictions (by providing a better depiction of the lateral plume spreading).
- Use of the modified AERMET (leading to higher u_*) reduces overpredictions, due to its inferred higher effective dilution wind speed and higher turbulence levels in the vertical and horizontal.
- Increased minimum sigma-v = 0.4 m/s produces clear improvement in model performance, especially at the highest concentrations (i.e., close arcs and/or lowest wind speeds).
- Biggest improvement to model performance occurs with the reformulated u_* in AERMET when the met data lack sigma-theta observations.
- The residual plots (not shown here) indicate that the model's performance trends from a slight overprediction bias (by a factor of ~1.5) at 100 meters to relatively unbiased at 200 and 400 meters for all model configurations.

Figure 12-3: Idaho Falls AERMOD Q-Q Plot: 1 Met Level, no Sigma-Theta using Current AERMET

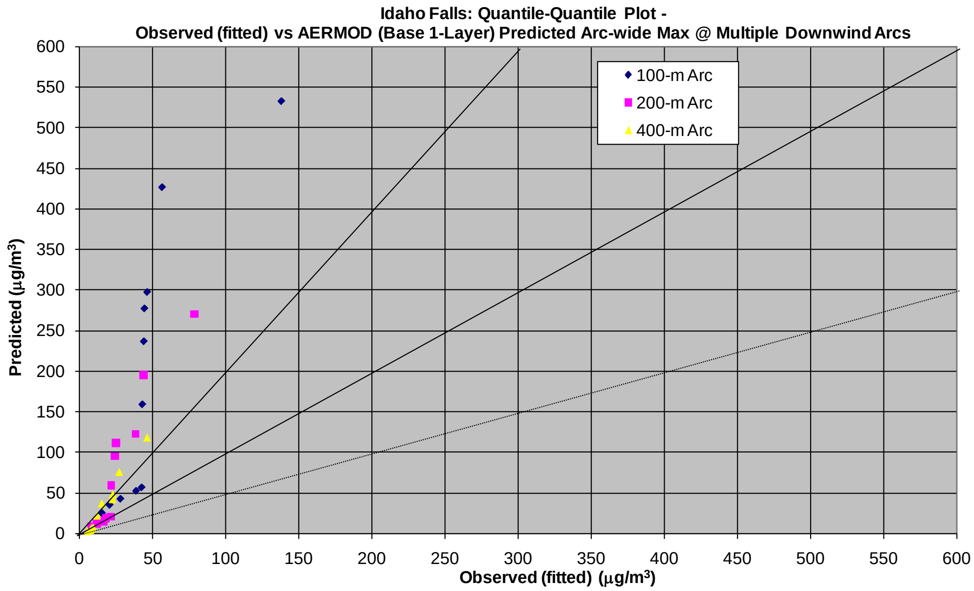


Figure 12-4: Idaho Falls: AERMOD Q-Q Plot: 1 Met Level, no Sigma-Theta using Improved AERMET u_* Formulation

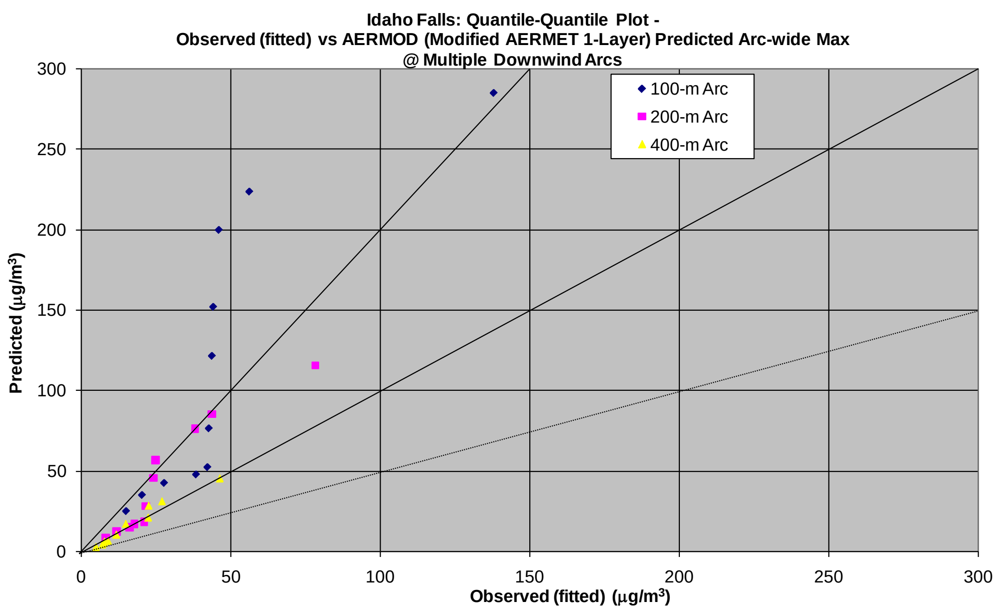


Figure 12-5: Idaho Falls AERMOD Q-Q Plot: 1 Met Level, no Sigma-Theta using Improved AERMET u_* Formulation and 0.4 m/s Minimum Sigma-v

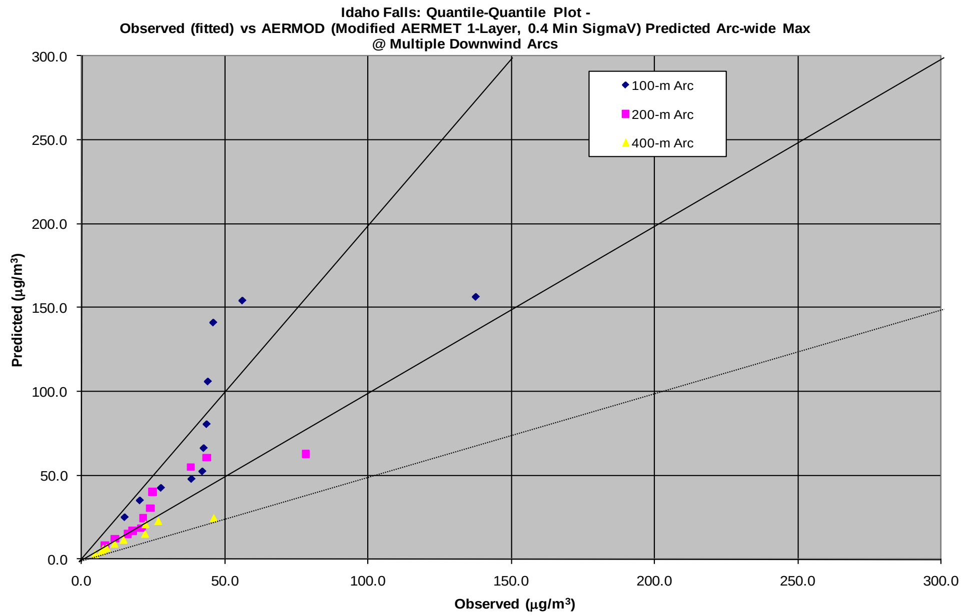


Figure 12-6: Idaho Falls AERMOD Q-Q Plot: 1 Met Level, with Observed Sigma-Theta using Current AERMET

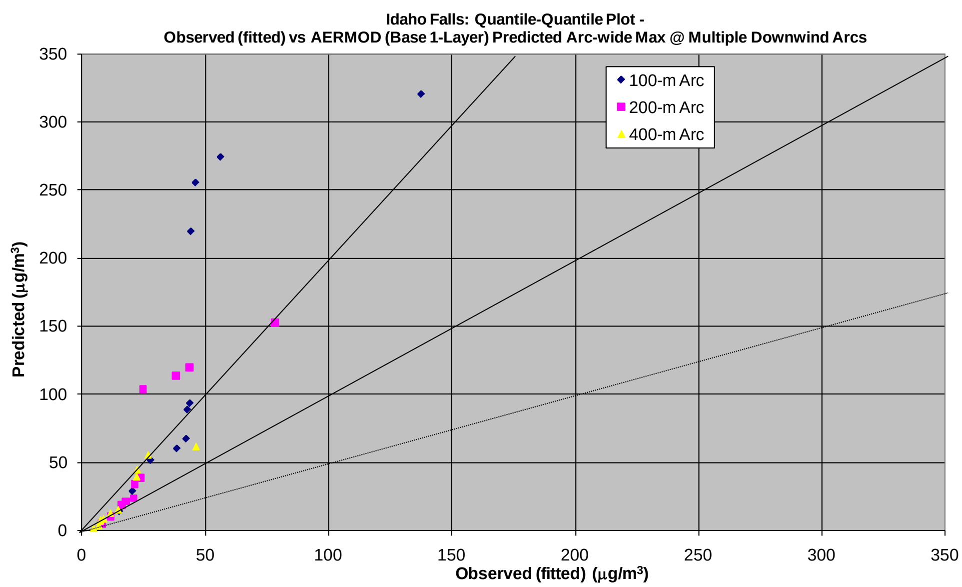


Figure 12-7: Idaho Falls AERMOD Q-Q Plot: 1 Met Level, with Observed Sigma-Theta using Improved AERMET u* Formulation

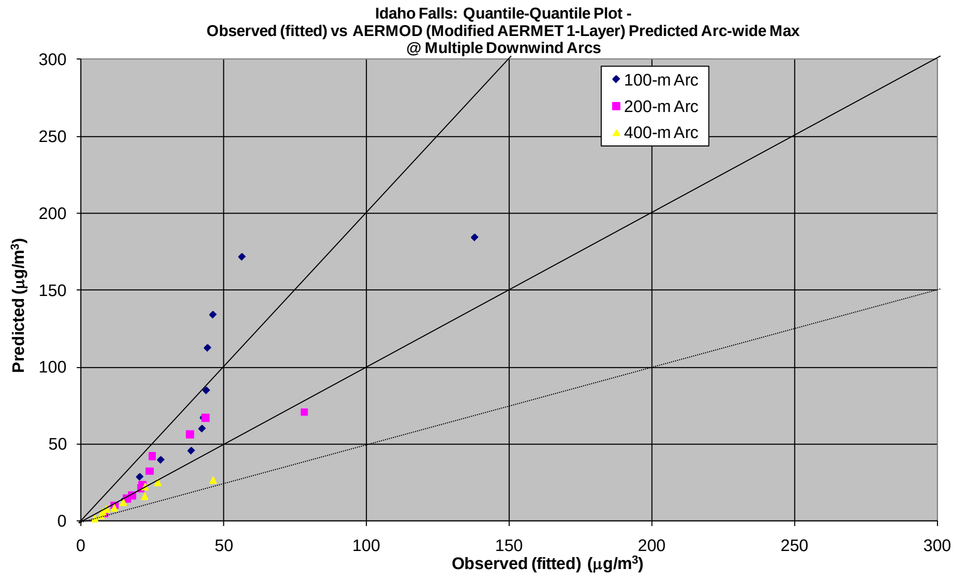


Figure 12-8: Idaho Falls AERMOD Q-Q Plot: 1 Met Level, with Observed Sigma-Theta using Improved AERMET u* Formulation and 0.4 m/s Minimum Sigma-v

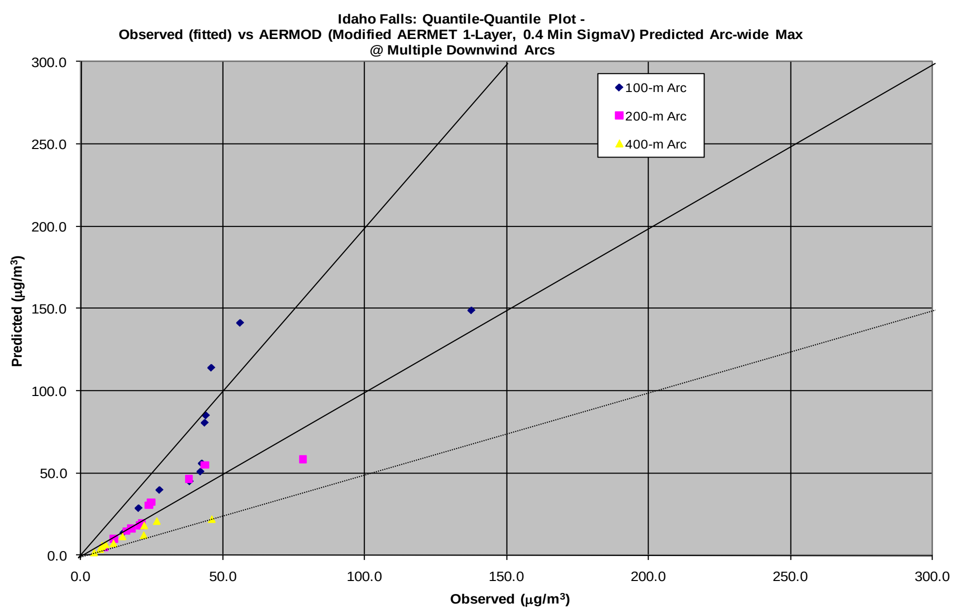


Figure 12-9: Idaho Falls AERMOD Q-Q Plot: 2 Met Levels, with Observed Sigma-Theta using Current AERMET

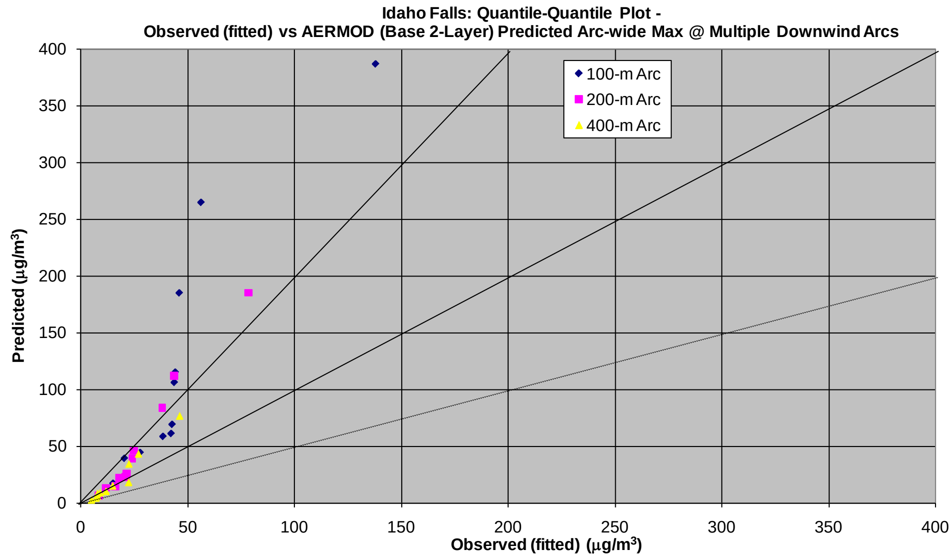


Figure 12-10: Idaho Falls AERMOD Q-Q Plot: 2 Met Levels, with Observed Sigma-Theta using Improved AERMET u_* Formulation

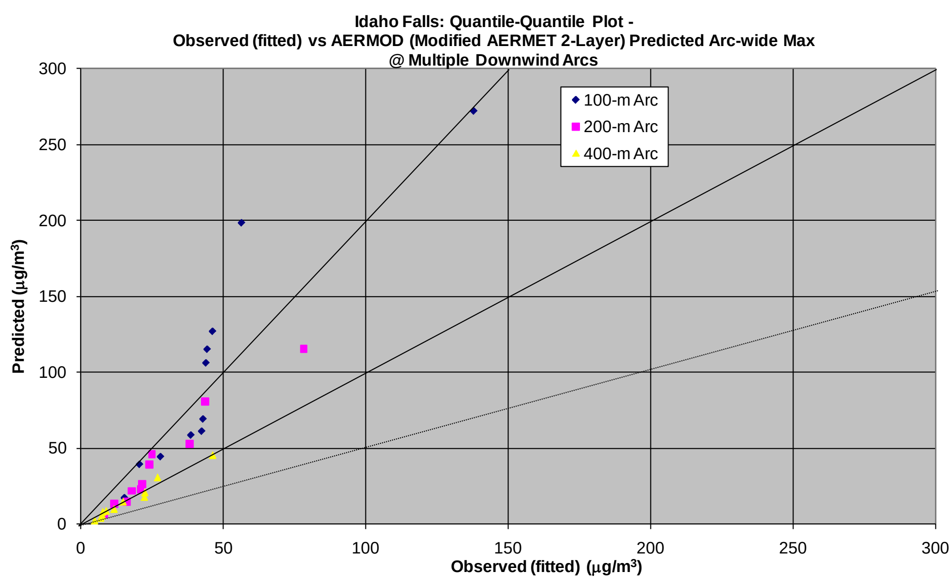
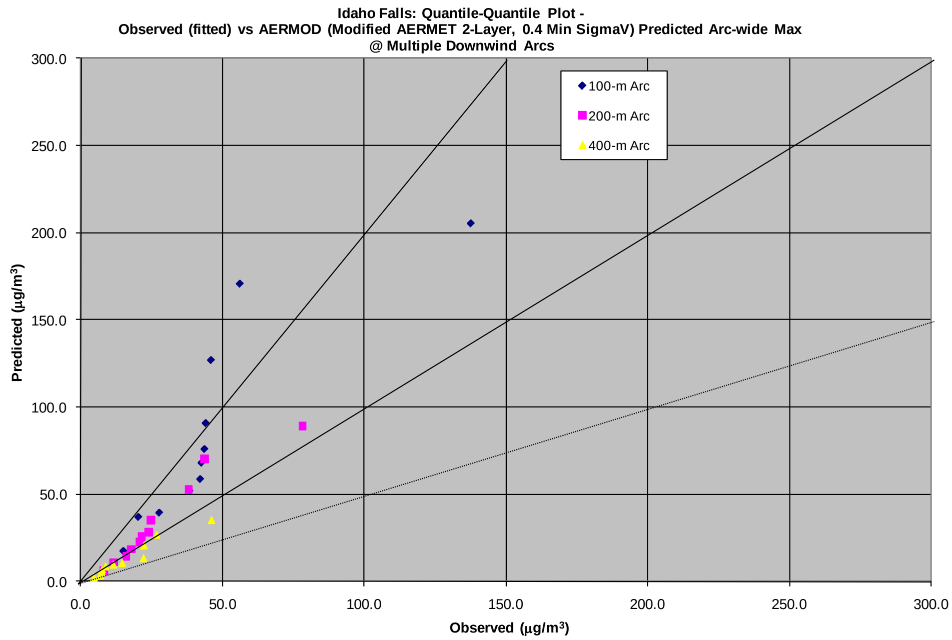


Figure 12-11: Idaho Falls AERMOD Q-Q Plot: 2 Met Levels, with Observed Sigma-Theta using Improved AERMET u* Formulation and 0.4 m/s Minimum Sigma-v



12.3 Oak Ridge: Non-Buoyant Low-Level Tracer Release

This database featured a mixture of stable and neutral to slightly convective hours (either before or shortly after sunrise in August), but with very low wind speeds. There was only one layer of meteorological data available, with no sigma-theta observations. Figures 12-12 and 12-13 present Q-Q plots of the AERMOD evaluations for the current and improved (modified u_*) AERMET assumptions, respectively.

The results of this evaluation to date are as follows:

- Substantial overpredictions occur, especially at closest distances without model improvements.
- The overpredictions mostly occur during stable hours.
- AERMOD does reasonably well for neutral/slightly unstable conditions.
- There is a need to account for the larger lateral spread of the plume during stable conditions.
- Use of reformulated AERMET (higher u_*) reduces overpredictions by approximately a factor of 2 by creating a higher effective dilution wind speed and higher levels of vertical and horizontal turbulence.
- Minimum sigma-v = 0.4 m/s (see Figure 12-14) substantially improves model performance.
- The residual plots (not shown here) indicate that the modeled-to-observed ratio does not significantly change as a function of distance for all model configurations.

Figure 12-12: Oak Ridge AERMOD Q-Q Plot: 1 Met Level using Current AERMET

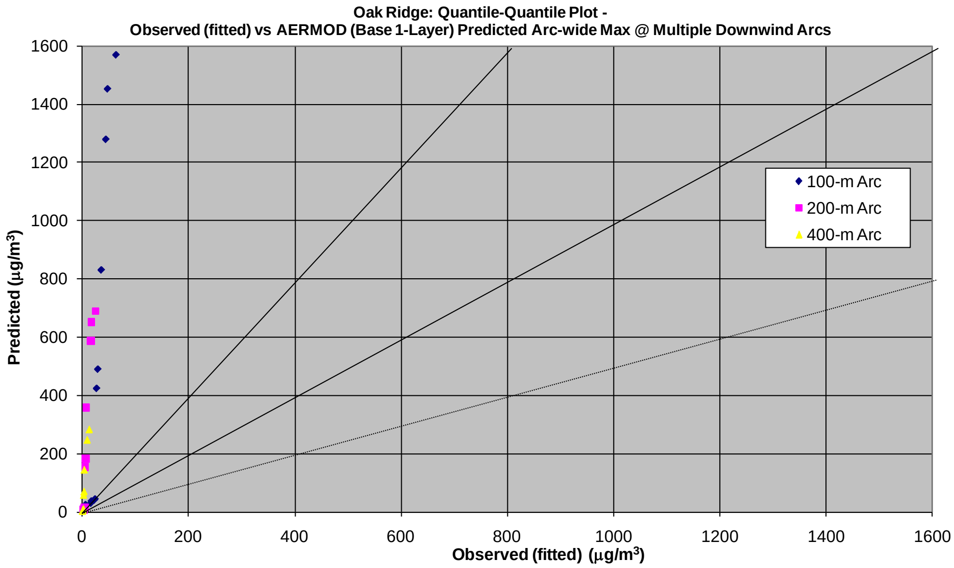


Figure 12-13: Oak Ridge AERMOD Q-Q Plot: 1 Met Level using Improved AERMET u* Formulation

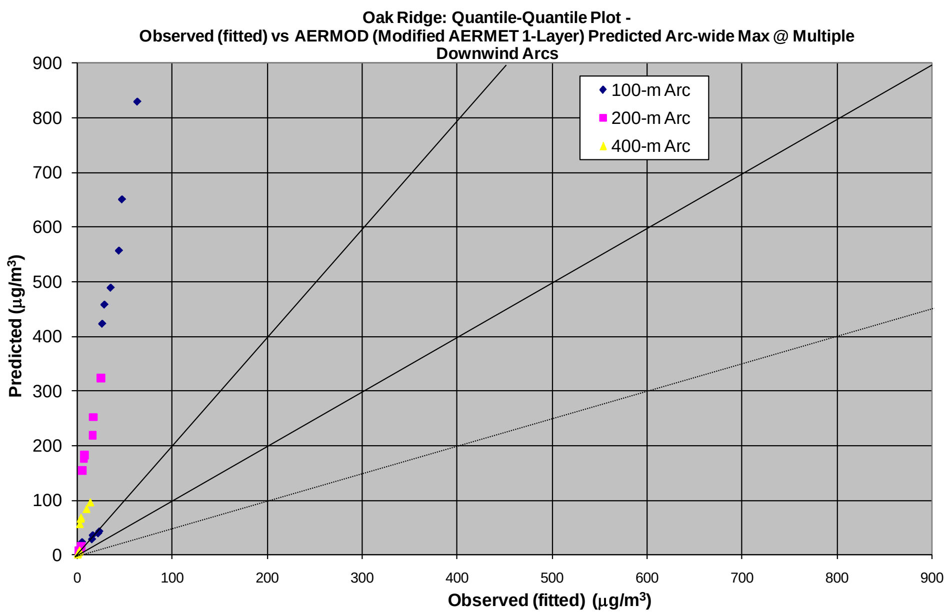
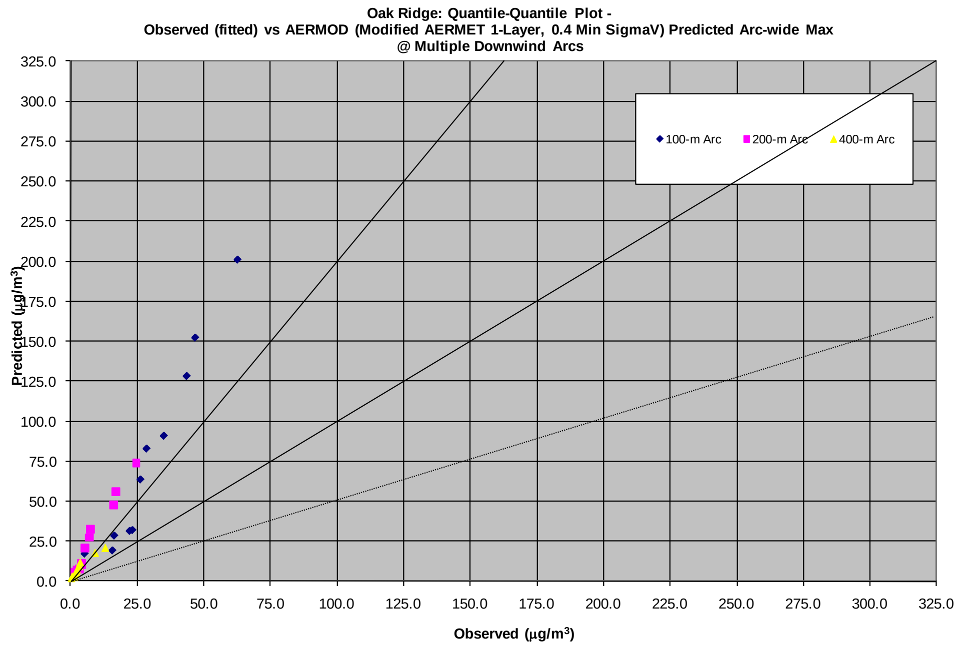


Figure 12-14: Oak Ridge AERMOD Q-Q Plot: 1 Met Level using Improved AERMET u* Formulation and 0.4 m/s Minimum Sigma-v



12.4 Summary

An AERMOD evaluation study has been completed that focuses upon low wind speed stable conditions. For the Bull Run field study, where releases were from a tall stack, no high concentrations were observed at ground level during stable conditions. For the Idaho Falls and Oak Ridge field studies, the releases were from low-level sources and very high concentrations were observed during stable conditions. The study has enhanced the evaluation history of AERMOD and provides additional confidence in a possible better performing version of AERMOD that could emerge from this study.

We have conducted evaluations with the current version of AERMET/AERMOD and with our improved versions (with enhanced u*) of AERMET/AERMOD. The evaluation results for the tall stack releases in unstable conditions for Bull Run are acceptable, and do not warrant further AERMOD model development at this time. AERMOD over-predicts for the Idaho Falls and Oak Ridge low wind stable conditions. But with observed sigma-theta, incorporation of minimum sigma-v = 0.4 m/s, and with the AERMET improvements to the u* estimate, the revised AERMOD has much improved performance.

At this time, we have formatted the AERMOD calculations for stable hours in spreadsheet form to facilitate further analysis with the Idaho Falls and Oak Ridge experiment trials. These calculations are being reviewed in order to suggest AERMOD improvements to USEPA. A primary focus of the improvements will be the lateral dispersion, especially in cases when sigma-theta observations are not available.

So far, we have found that the improvements to the AERMET methodology for calculation of u*, the use of observed sigma-theta, and the use of an increased minimum sigma-v (from 0.2 to 0.4 m/s) leads to better model performance.

13.0 Limited CALPUFF Evaluation

As part of the low wind speed study, a limited evaluation of the CALPUFF model was also conducted. CALPUFF was evaluated using the AERMOD-ready meteorological data developed during the AERMOD portion of the low wind speed model evaluation. The same modeled emissions, receptors, and terrain data used for the AERMOD evaluation were assumed for the CALPUFF model evaluation.

The CALPUFF model evaluation was focused upon the two low-level non buoyant experiments, Idaho Falls and Oak Ridge. CALPUFF was in a manner such that the dispersion would be as consistent as possible with AERMOD. Thus the following CALPUFF options were used for this portion of the low wind speed evaluation:

1. MDISP =2, for turbulence based dispersion (with the standard CALPUFF sub-routines)
2. MPDF = 1, it is recommended by the model developer that the partial density function be turned on when turbulence based dispersion is selected
3. MCHEM = 0, atmospheric chemistry was turned off
4. MWET and MDRY = 0, wet and dry removal not modeled

As stated previously, AERMOD was evaluated for the following three model configurations:

- **Base Model → Current AERMET and AERMOD**
- **Modified AERMET →** new AERMET (with updated u_* formulation) and current AERMOD
- **Higher Minimum Sigma-v →** new AERMET (with updated u_* formulation and new AERMOD versions with minimum sigma-v increased from 0.2 to 0.4,

CALPUFF was evaluated for two the candidate model configurations that showed the best model performance of the three mentioned above; they are:

(1) **Modified AERMET →** new AERMET (with updated u_* formulation) and current AERMOD

(2) **Higher Minimum Sigma-v →** new AERMET (with update u_* formulation and new AERMOD versions with minimum sigma-v increased from 0.2 to 0.4

The CALPUFF model performance was rated using the same ranked predicted versus observed arc-wide maximum concentrations plotted on a quantile-quantile plot.

Figures 13-1 through 13-6 present the CALPUFF model evaluation results for the Idaho Falls experiment. The Idaho Falls results are presented for the same three meteorological processing options and two of the three model configurations (as noted above) used in the AERMOD portion of the low wind speed study.

Likewise, for Oak Ridge, Figures 13-7 and 13-8 present the CALPUFF model evaluation results for the Oak Ridge experiments. The Oak Ridge results are presented for two of the three model configurations (as noted above) used in the AERMOD portion of the low wind speed study.

In addition to the results plotted below, some sensitivity analysis with the CALPUFF model was also tested. The sensitivity of the models performance was tested for the following CALPUFF model options:

(1) AERMOD turbulence based dispersion parameters as opposed to CALPUFF – The results were shown to be very insensitive to this CALPUFF model option. The modeled predictions hardly changed at all.

(2) Decrease (from 0.5 to 0.4) of CALPUFF's minimum sigma-v (SVMIN) – The results was shown to generally lower to model's predictions.

The CALPUFF model results generally show that CALPUFF is under predicting relative to AERMOD by a factor of 1.5 to 2 for similar meteorological inputs and model configurations. This results in underprediction relative to observations for Idaho Falls by about a factor of 2, but less of an overprediction (reduced to about a factor of 2) for Oak Ridge.

Figure 13-1: Idaho Falls CALPUFF Q-Q Plot: 1 Met Level, no Sigma-Theta using Improved AERMET u_* Formulation

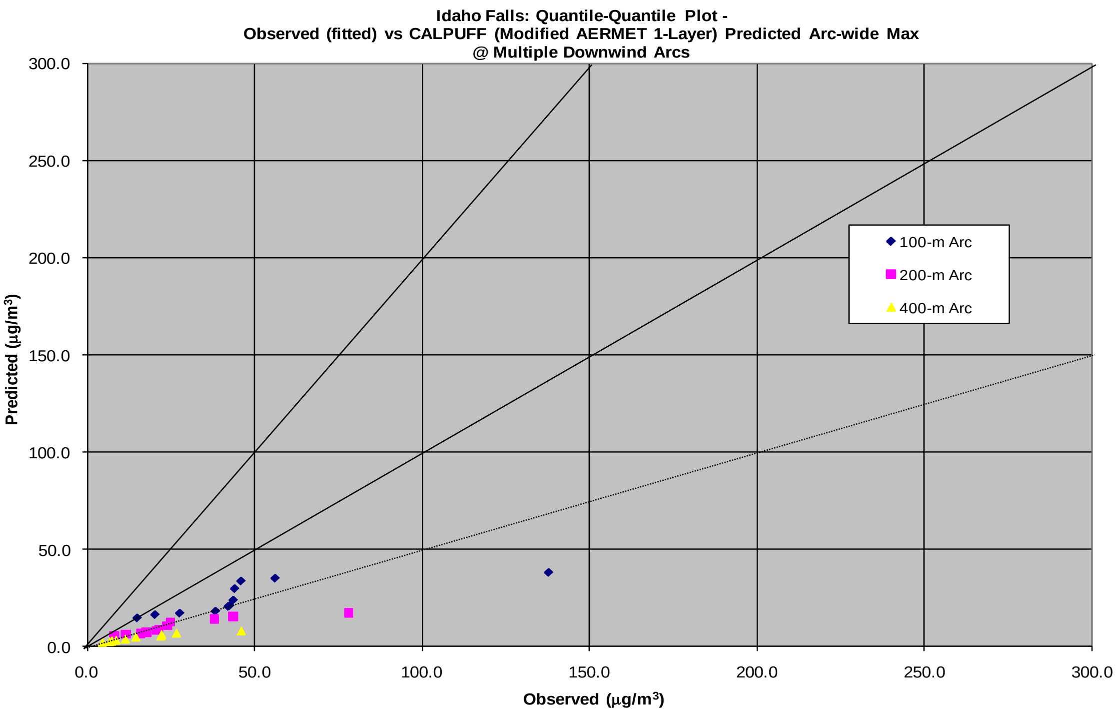


Figure 13-2: Idaho Falls CALPUFF Q-Q Plot: 1 Met Level, no Sigma-Theta using Improved AERMET u_* Formulation and 0.4 Minimum Sigma-v

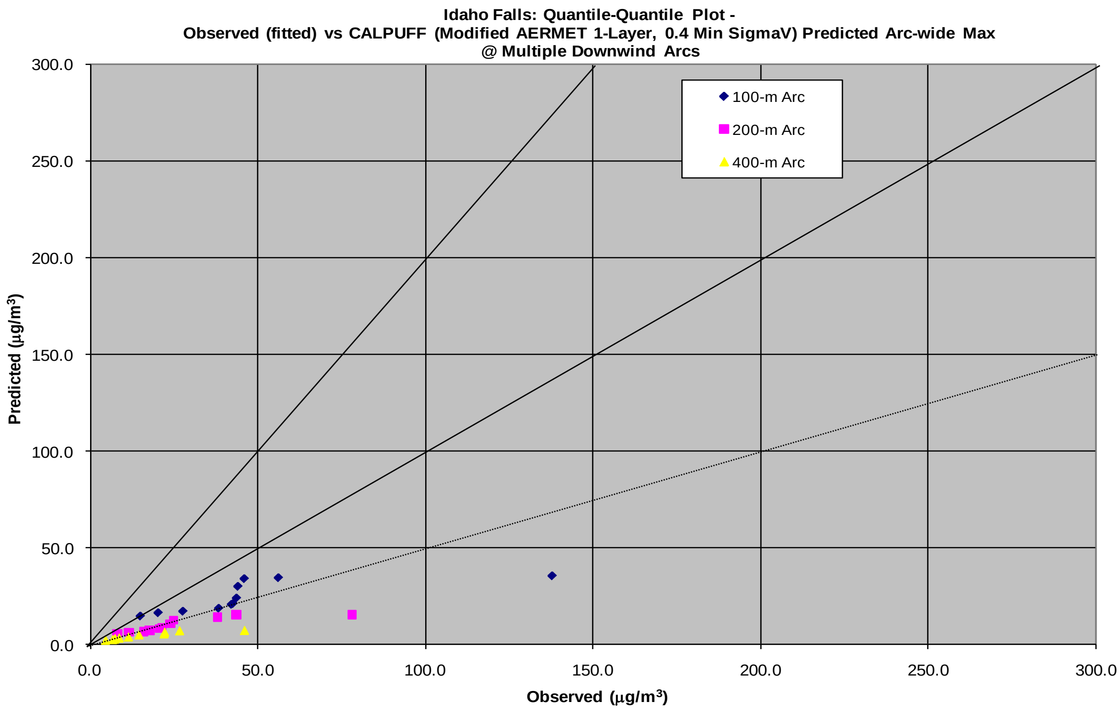


Figure 13-3: Idaho Falls CALPUFF Q-Q Plot: 1 Met Level, with Sigma-Theta using Improved AERMET u_* Formulation

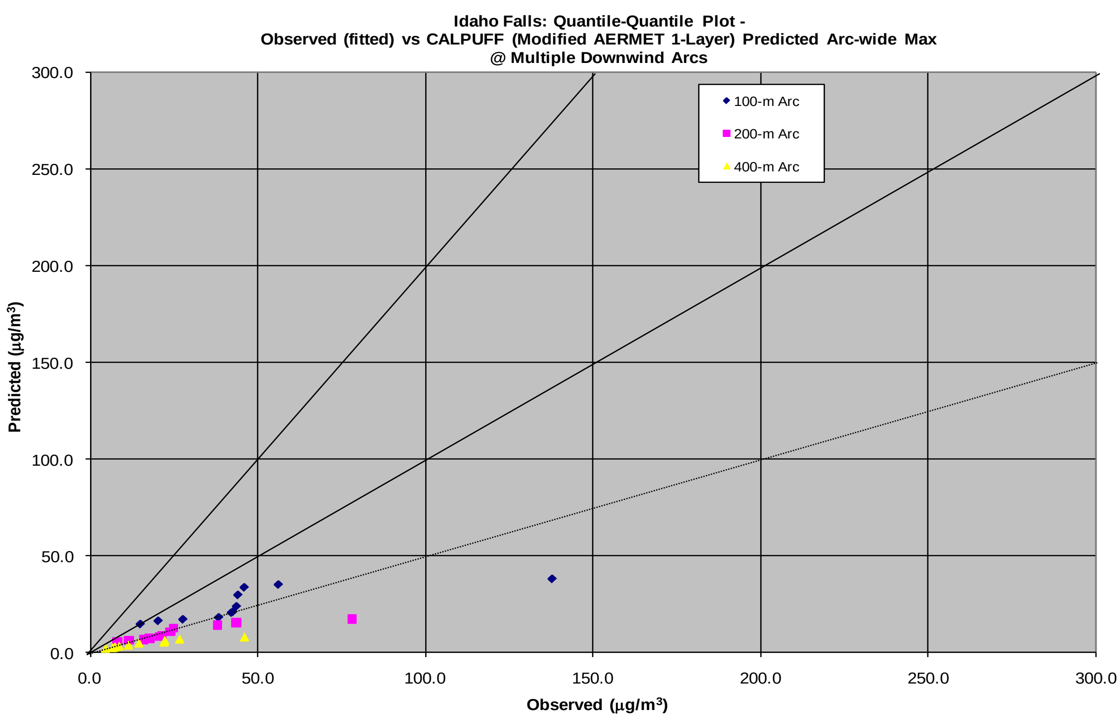


Figure 13-4: Idaho Falls CALPUFF Q-Q Plot: 1 Met Level, with Sigma-Theta using Improved AERMET u* Formulation and 0.4 Minimum Sigma-v

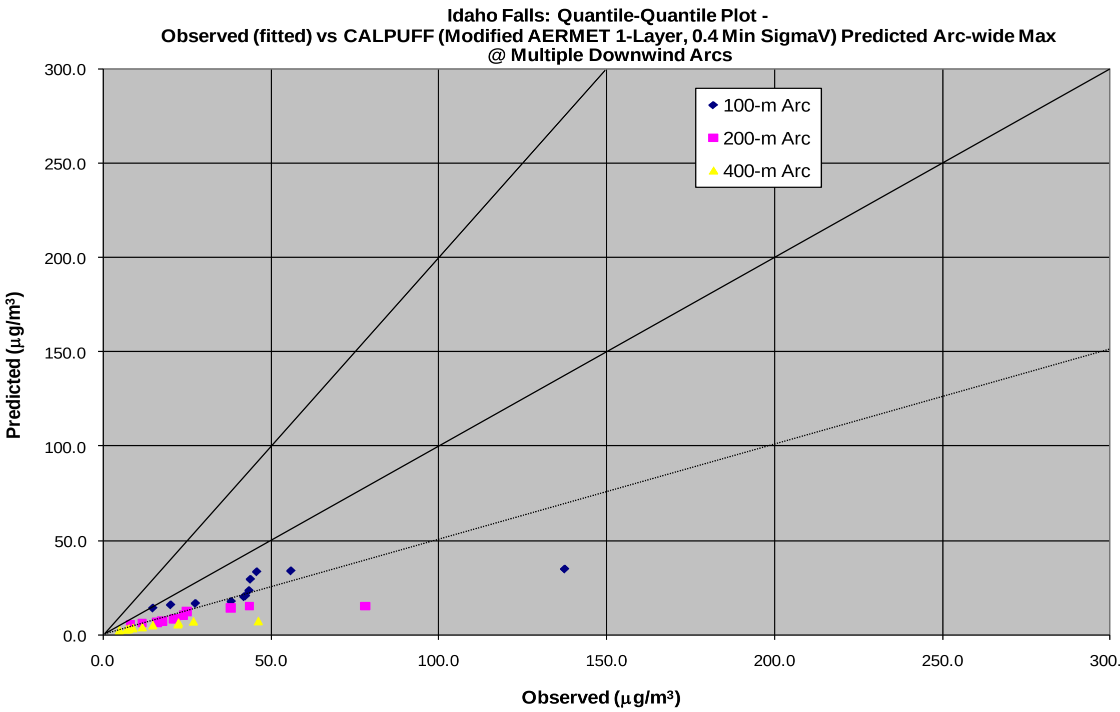


Figure 13-5: Idaho Falls CALPUFF Q-Q Plot: 2 Met Levels, with Sigma-Theta using Improved AERMET u* Formulation

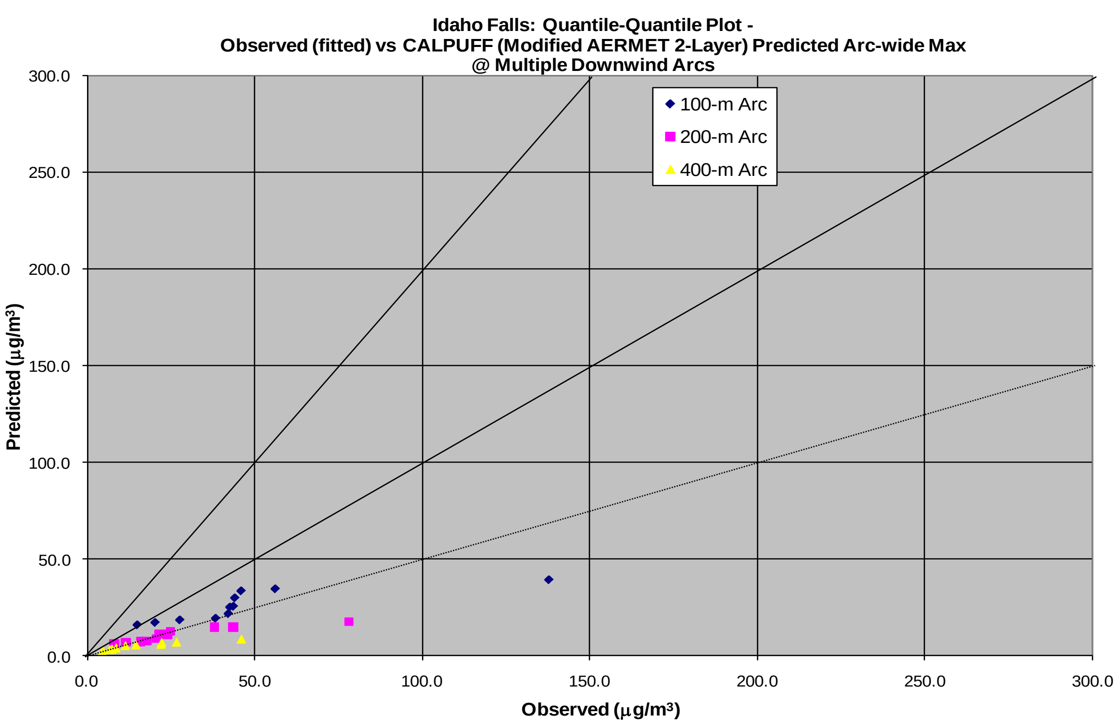


Figure 13-6: Idaho Falls CALPUFF Q-Q Plot: 2 Met Levels, with Sigma-Theta using Improved AERMET u* Formulation and 0.4 Minimum Sigma-v

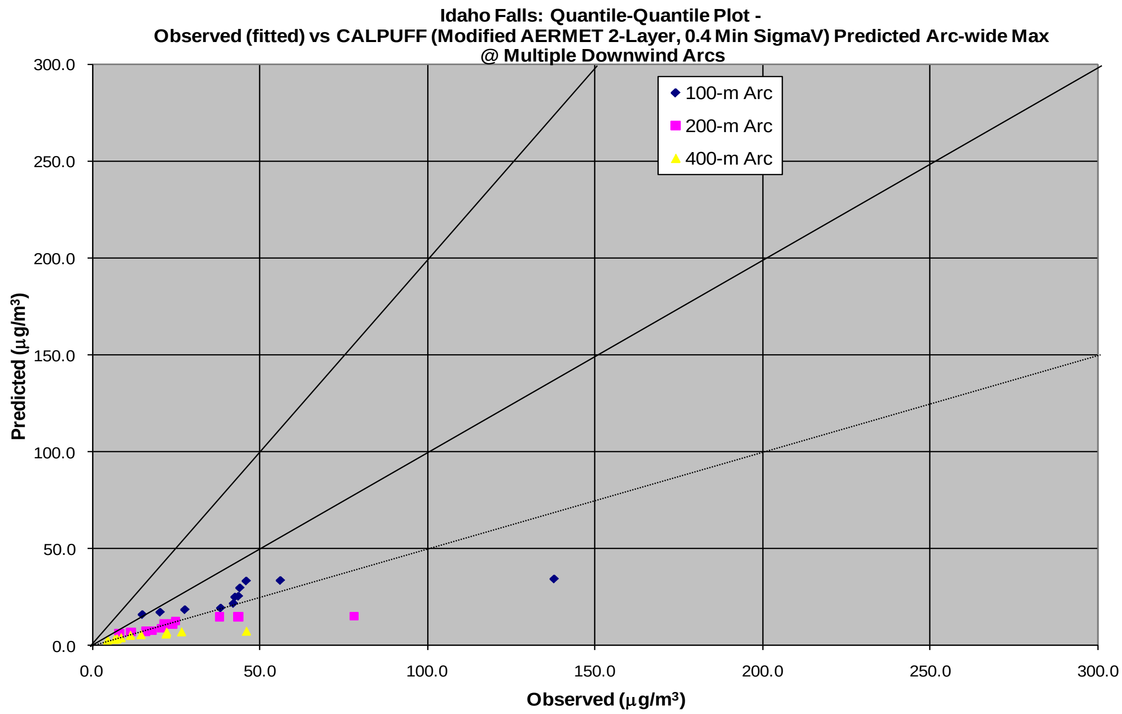


Figure 13-7: Oak Ridge CALPUFF Q-Q Plot: 1 Met Level using Improved AERMET u* Formulation

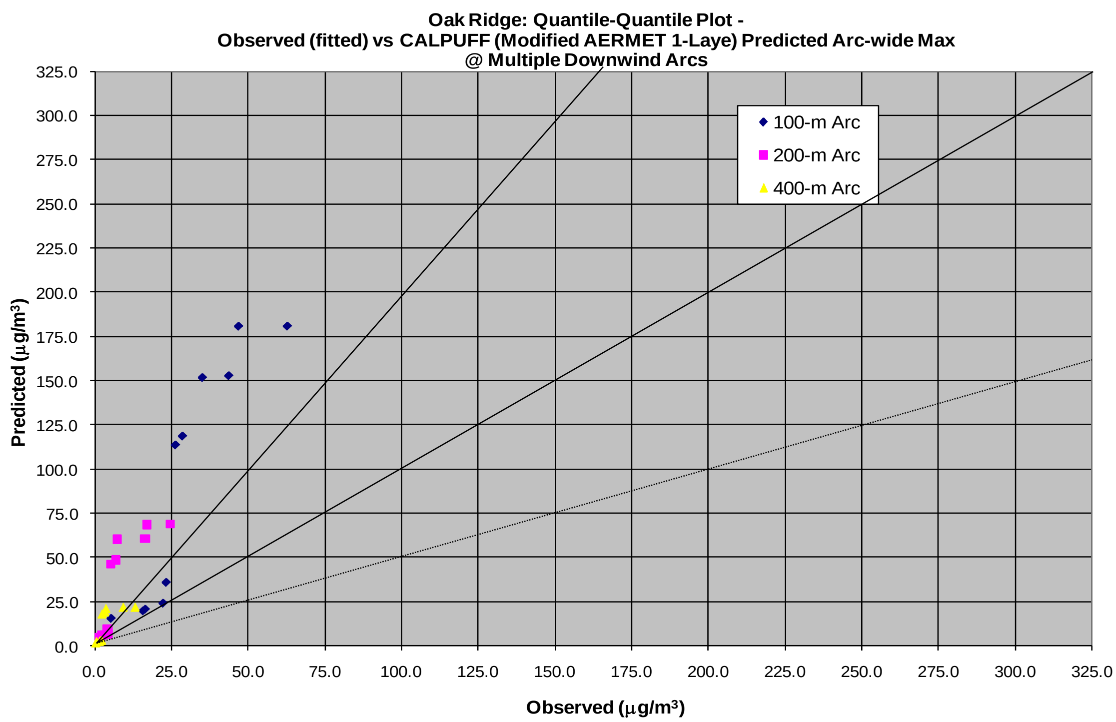
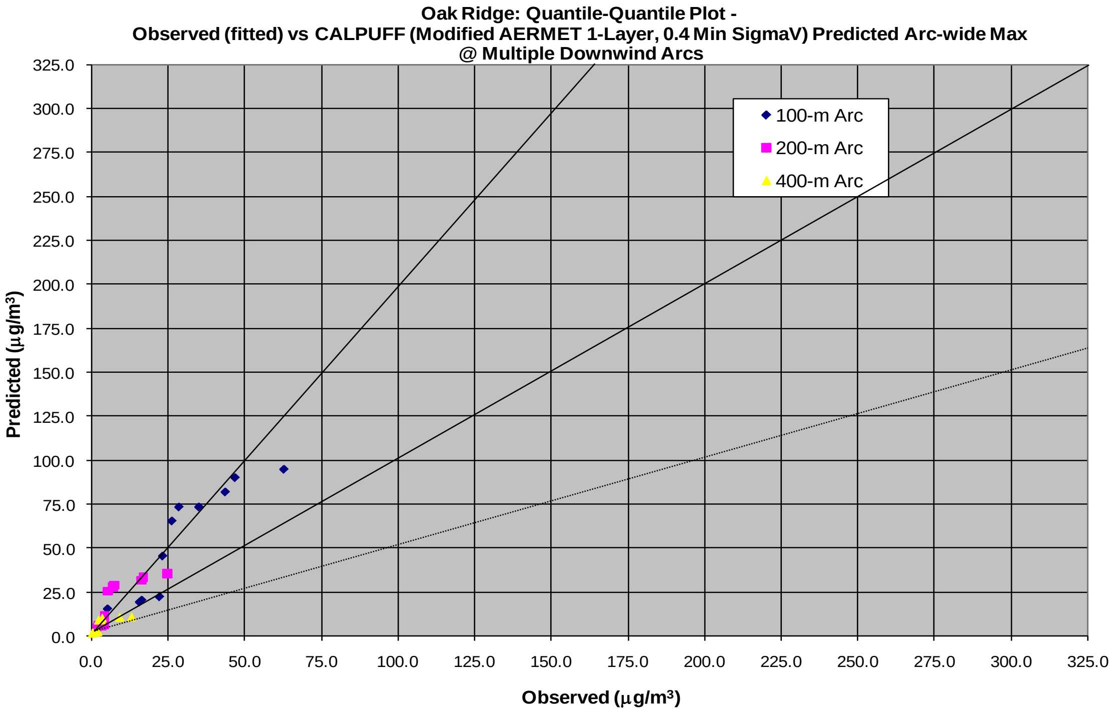


Figure 13-8: Oak Ridge CALPUFF Q-Q Plot: 1 Met Level using Improved AERMET u_* Formulation and 0.4 Minimum Sigma-v



14.0 References

1. U.S. Environmental Protection Agency, 2004. User's Guide for the AERMOD Meteorological Processor (AERMET) EPA Document No. EPA-454/B-03-002. Office of Air Quality Planning and Standards, Research Triangle Park, NC.

2. Scire, J. S., D. G. Strimaitis, R. J. Yamartino, 2000. A User's Guide for the CALPUFF Dispersion Model (Version 5). Earth Tech, Inc. Concord, Massachusetts.

3. U.S. Environmental Protection Agency, 2007. AERMOD Implementation Workgroup. Presented at the EPA 2007 Modelers Workshop. http://www.cleanairinfo.com/regionalstatelocalmodelingworkshop/old/2007/presentations/Tuesday%20-%20May%2015%202007/AERMOD_Implementation_Workgroup.pdf.

4. Rayner, K, 2007. Personal communication with Robert Paine of AECOM.

5. Liebsch, E. and E. Grimm, 2005. Comparison of ISCST3 and AERMOD Results for Fugitive Dust Sources. Paper #625, presented at the 98th Annual Conference & Exhibition of the Air & Waste Management Association, Minneapolis, MN.

6. Olesen, H., R. Berkowicz, and P. Løfstrøm, 2007. Evaluation of OML and AERMOD. Presented at the Proceedings of the 11th International Conference on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes. Cambridge, UK.

7. Bowne, N. E., R. Londergan, D. Murray, 1984. Summary of the Results and Conclusions for the EPRI Plume Model Validation and Development: Moderately Complex Terrain Site. TRC Environmental Consultants.

8. Luhar AK, P.J. Hurley, and K.N. Rayner, 2009. Modelling near-surface low winds over land under stable conditions: sensitivity tests, flux-gradient relationships, and stability parameters. Boundary-Layer Meteorology. 130:249–274. DOI 10.1007/s10546-008-9341-7.

9. Luhar A.K. and K. N. Rayner, 2009. Methods to Estimate Surface Fluxes of Momentum and Heat from Routine Weather Observations for Dispersion Applications under Stable Stratification. Boundary-Layer Meteorology. 132:437–454.

10. Hanna S.R and J.C. Chang, 1993. Hybrid Plume Dispersion Model (HPDM) improvements and testing at three field sites. Atmos. Environ. 27A:1491-1508.

11. Cimorelli, A.J., S.G. Perry, A.Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, R.W. Brode, and J.O. Paumier, 2004. AERMOD: Description of Model Formulation. EPA-454/R-03-004.

12. Pickard, Lowe, and Associates, Inc., 1972. The Research Corporation of New England. General Public Utilities Service Corporation. Atmospheric Diffusion Experiments with SF6 Tracer Gas at Three Mile Island Nuclear Station Under Low Wind Speed Inversion Conditions.

13. NOAA Technical Memorandum ERL ARL-61, 1976. Diffusion under Low Wind Speed Conditions near Oak Ridge, Tennessee. Wilson, R. B., G. Start, C. Dickson, N. Ricks. Air Resources Laboratory, Idaho Falls, Idaho.

14. NOAA Technical Memorandum ERL ARL-52, 1974. Diffusion under Low Wind Speed, Inversion Conditions. Sagendorf, J. F., C. Dickson. Air Resources Laboratory, Idaho Falls, Idaho.

15. U.S. Environmental Protection Agency, 1992. Stagnation Diffusion Observed in a Deeply Pooling Valley During STAGMAP. EPA Document No. EPA/600/A-92/233. Briggs, G. A., Atmospheric Sciences Modeling Division, Air Resources Laboratory, National Oceanic and Atmospheric Administration, Research Triangle Park, NC.

16. Sharan, M., Singh, M.P., Yadav, A.K., Agarwal, P., Nigam, S., 1996. A Mathematical Model for Dispersion of Air Pollutants in Low Wind Conditions. Atm. Env. 30, 1209–1220.

17. Agarwal P., Yadav A. K., Gulati A., Raman S., Rao S., Singh M. P., Nigam S. and Reddy N., 1995. Surface Layer Turbulence Processes in Low Wind Speeds Over Land. Atm. Env. 29, 2089-2098.

18. VanderHoven, I.,1976. A Survey of Field Experiments of Atmospheric Diffusion under Low-Wind Speed Inversion Conditions. Nuc. Safety 17, no 2. 223-230.

19. Hanna S.R., 1990. Lateral dispersion in light wind stable conditions. Il Nuovo Cimento 13, 889-894.

20. Ermak, D.L., 1990. User's Manual for SLAB: An Atmospheric Dispersion Model for Denser-Than-Air Releases. Document UCRL-MA-105607, Lawrence Livermoor National Laboratory.

21. U.S. Environmental Protection Agency, 2003. AERMOD: Latest Features and Evaluation Results. EPA-454/R-03-003. Available at http://www.epa.gov/scram001/7thconf/aermod/eval.pdf.

22. Chang, J.C. and Hanna, S.R., 2004. Air Quality Model Performance. Meteorol. and Atmos. Physics 87, 167-196.

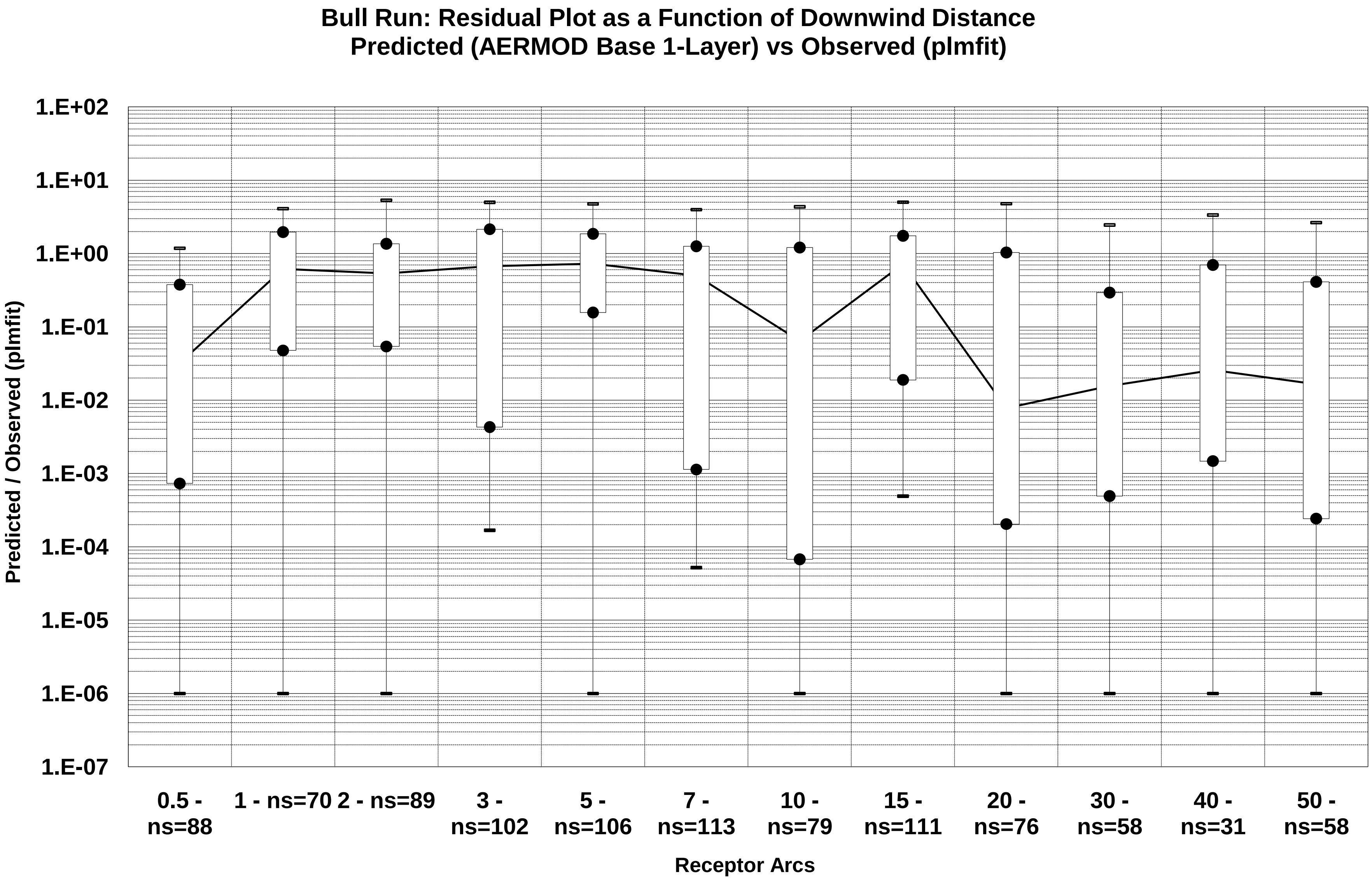
23. Chambers, J. M., Cleveland, W. S., Kleiner, B., and Tukey, P.A., 1983. Comparing Data Distributions. Graphical Methods for Data Analysis. (Bell Laboratories). Wadsworth International Group and Duxbury Press.

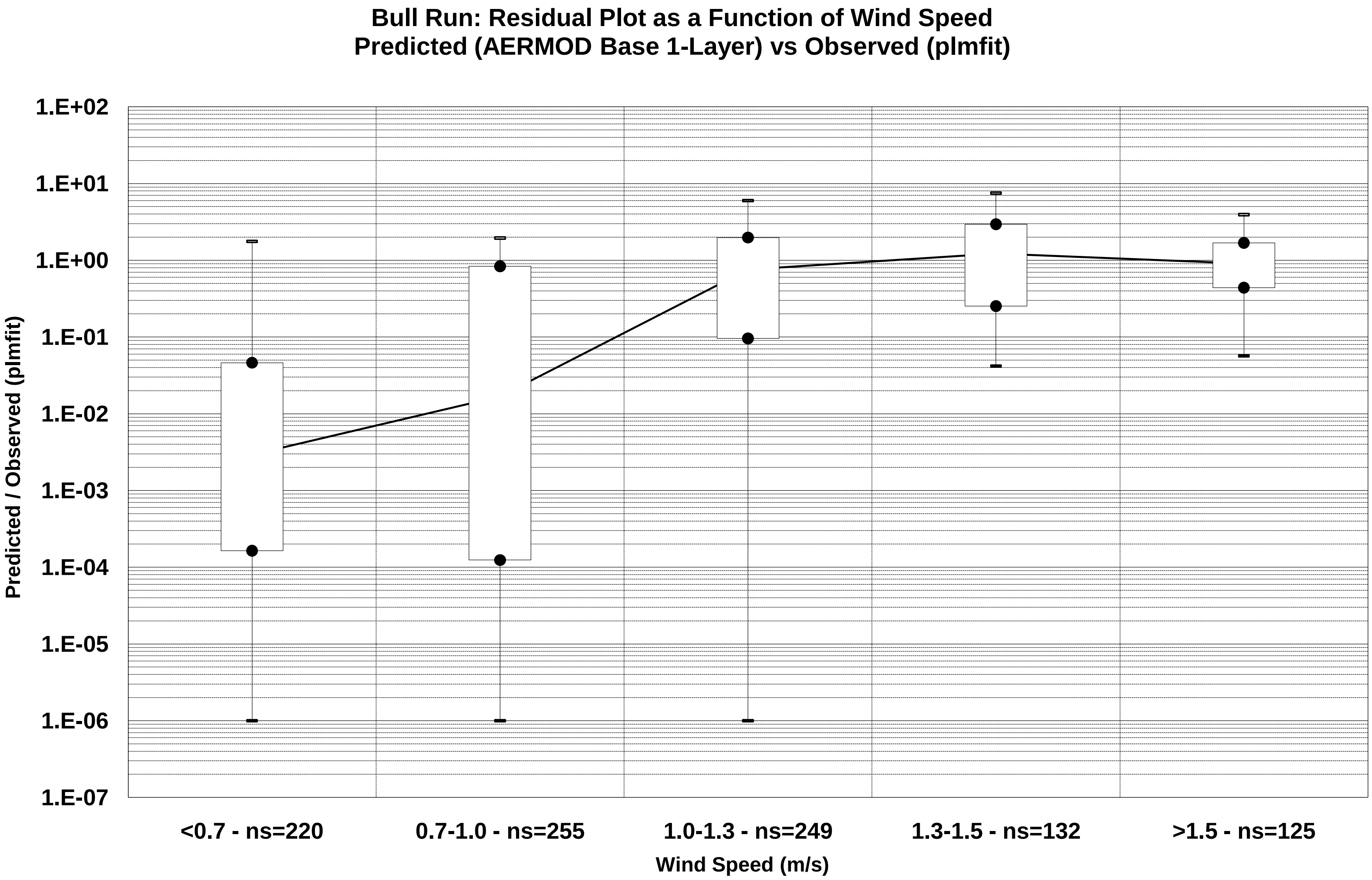
Appendix A

Model Evaluation Residual Plots

Bull Run Residual Plots

AERMOD

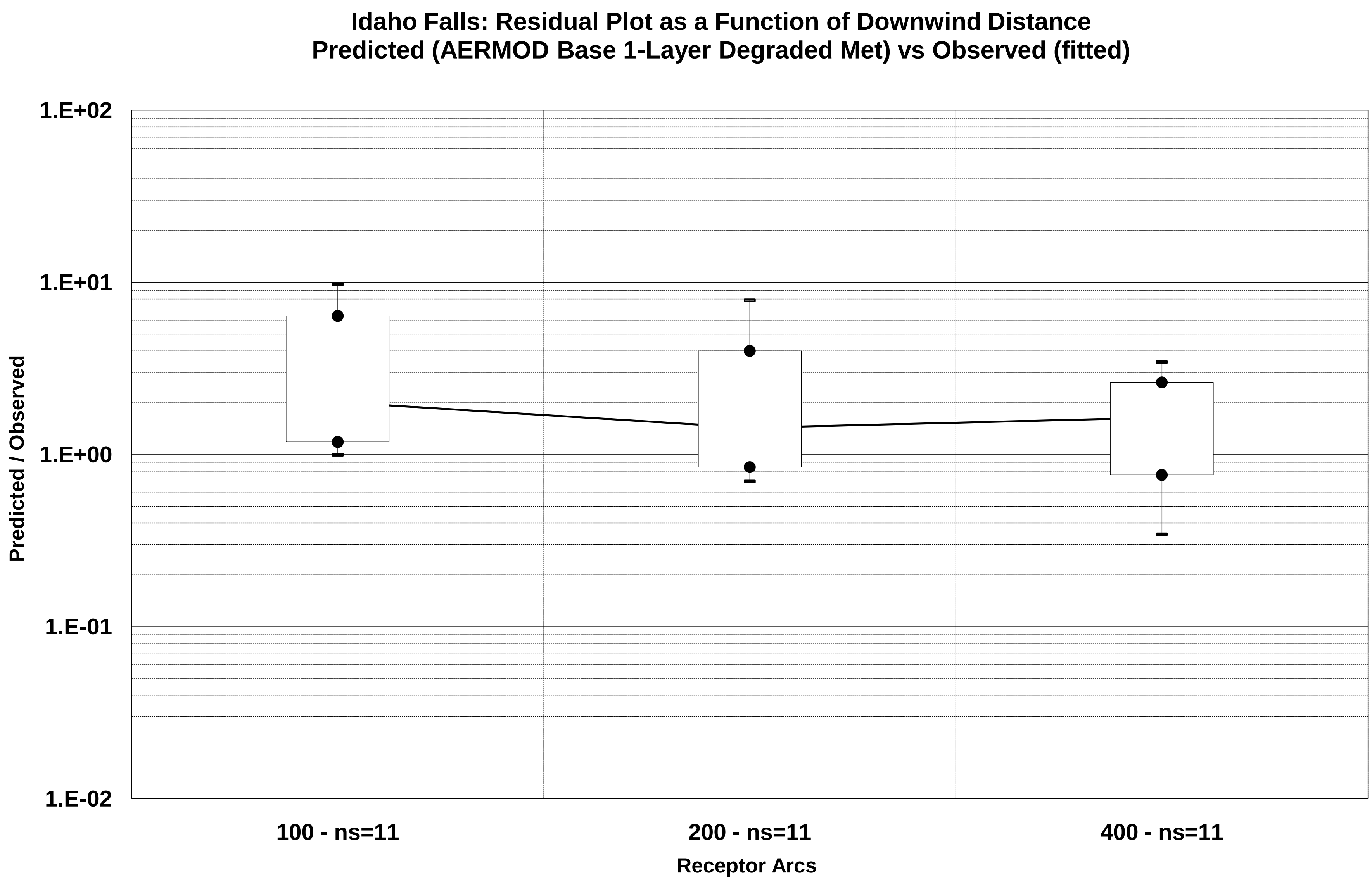

Bull Run: Residual Plot as a Function of Downwind Distance
Predicted (AERMOD Base 1-Layer) vs Observed (plmfit)
Predicted / Observed (plmfit)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
0.5 - ns=88
1 - ns=70
2 - ns=89
3 - ns=102
5 - ns=106
7 - ns=113
10 - ns=79
15 - ns=111
20 - ns=76
30 - ns=58
40 - ns=31
50 - ns=58
Receptor Arcs



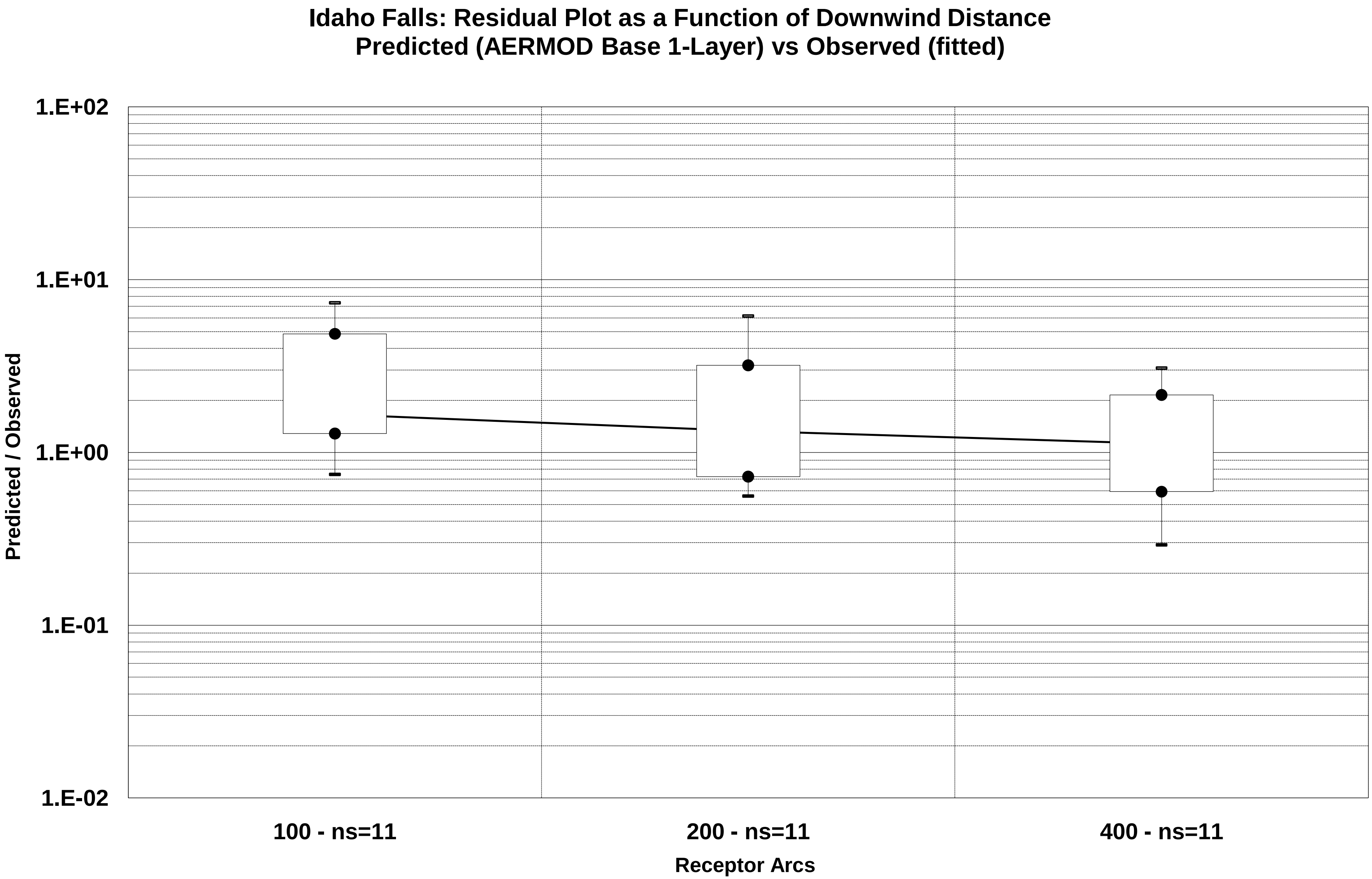
Bull Run: Residual Plot as a Function of Wind Speed
Predicted (AERMOD Base 1-Layer) vs Observed (plmfit)
Predicted / Observed (plmfit)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
<0.7 - ns=220
0.7-1.0 - ns=255
1.0-1.3 - ns=249
1.3-1.5 - ns=132
>1.5 - ns=125
Wind Speed (m/s)

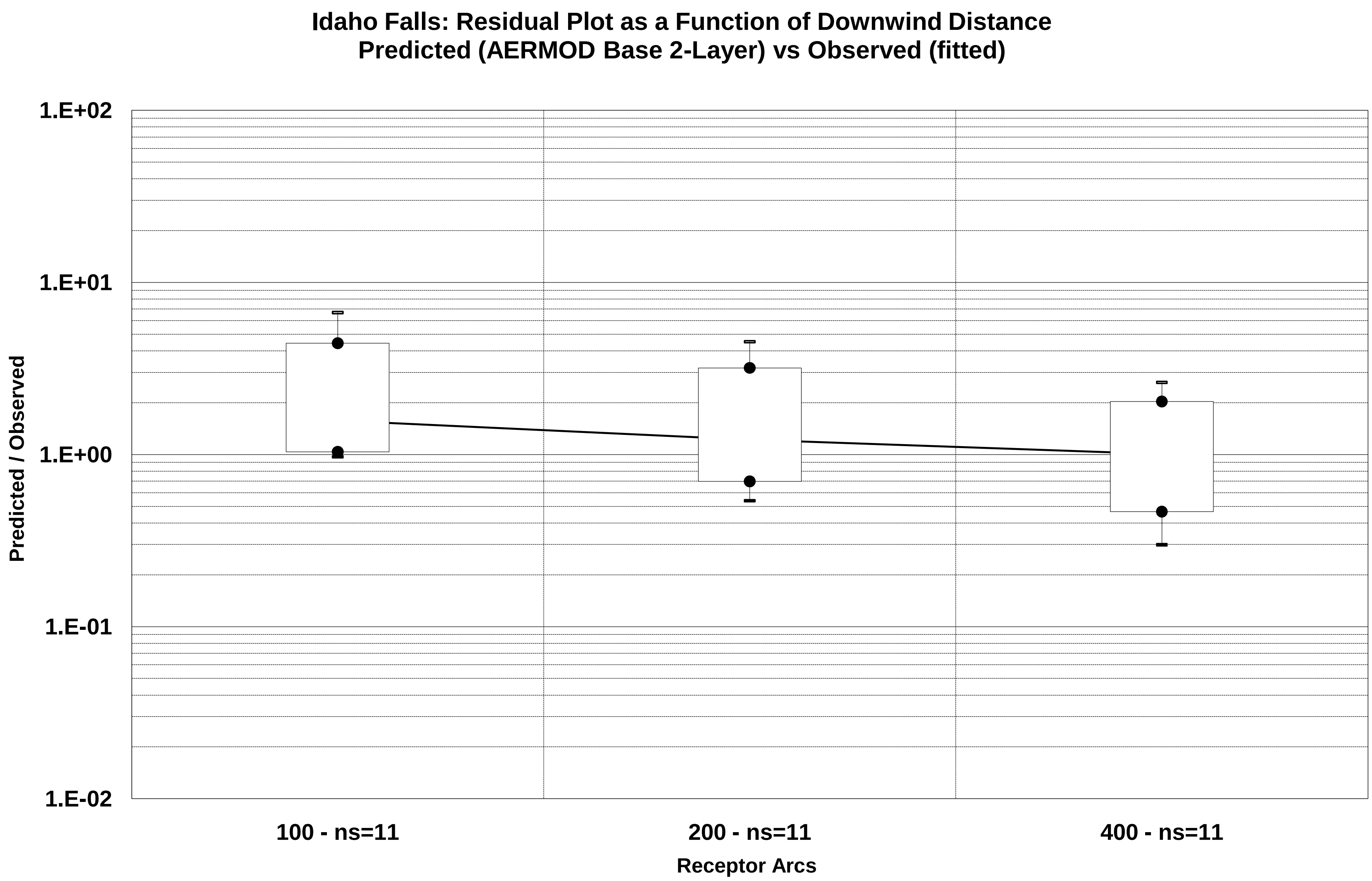
Idaho Falls Residual Plots

AERMOD

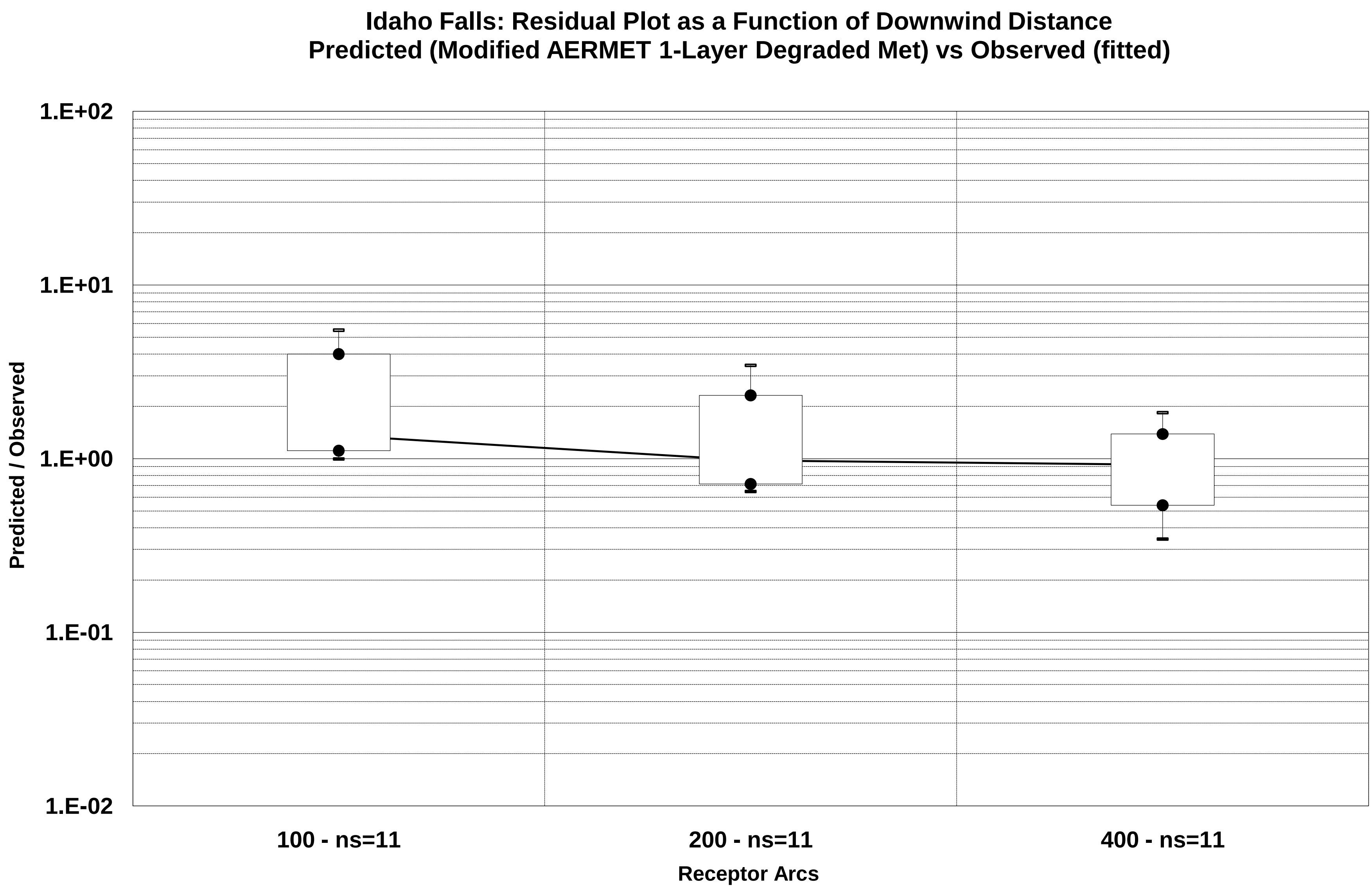


Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (AERMOD Base 1-Layer Degraded Met) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

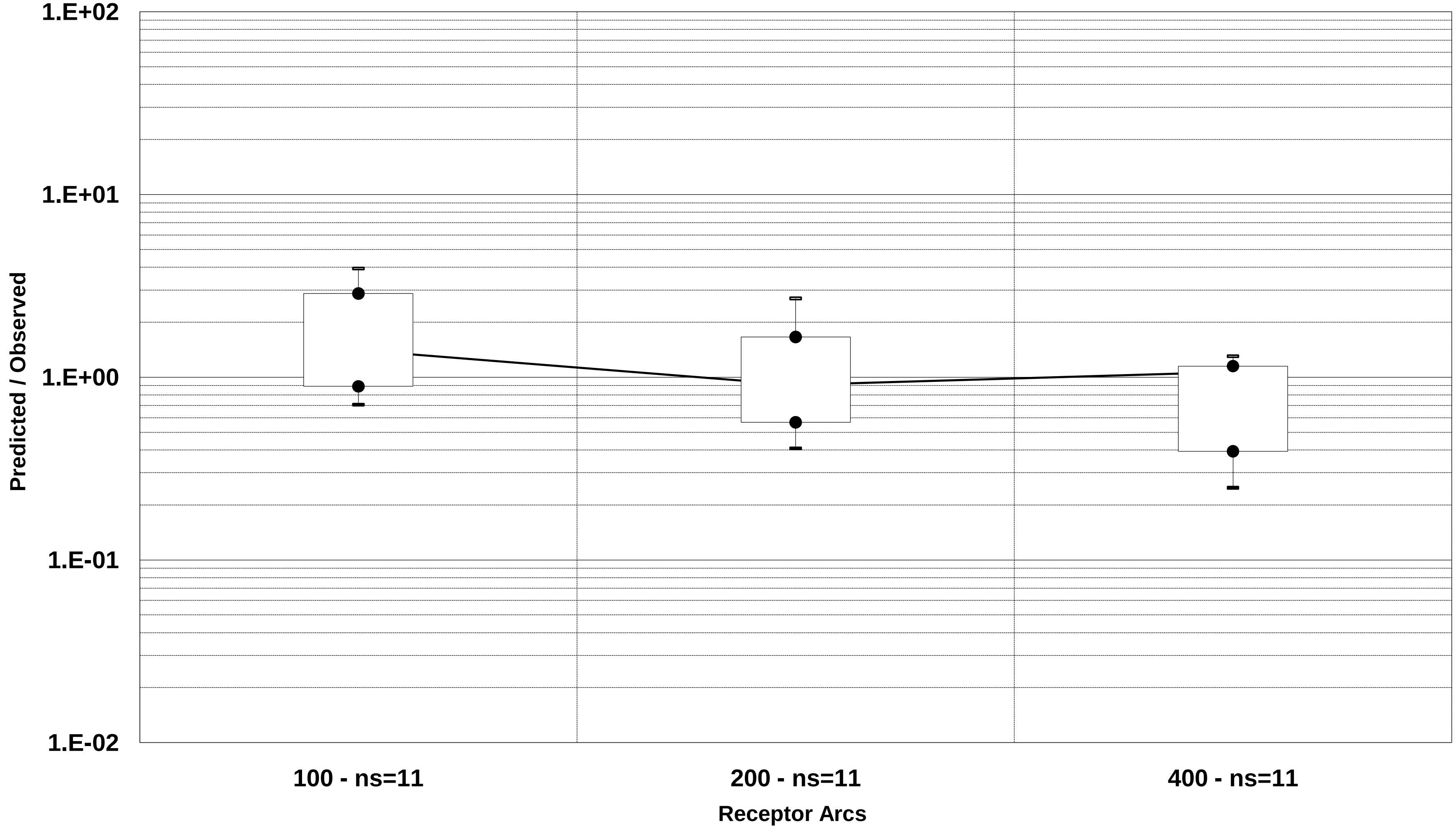

Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (AERMOD Base 1-Layer) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

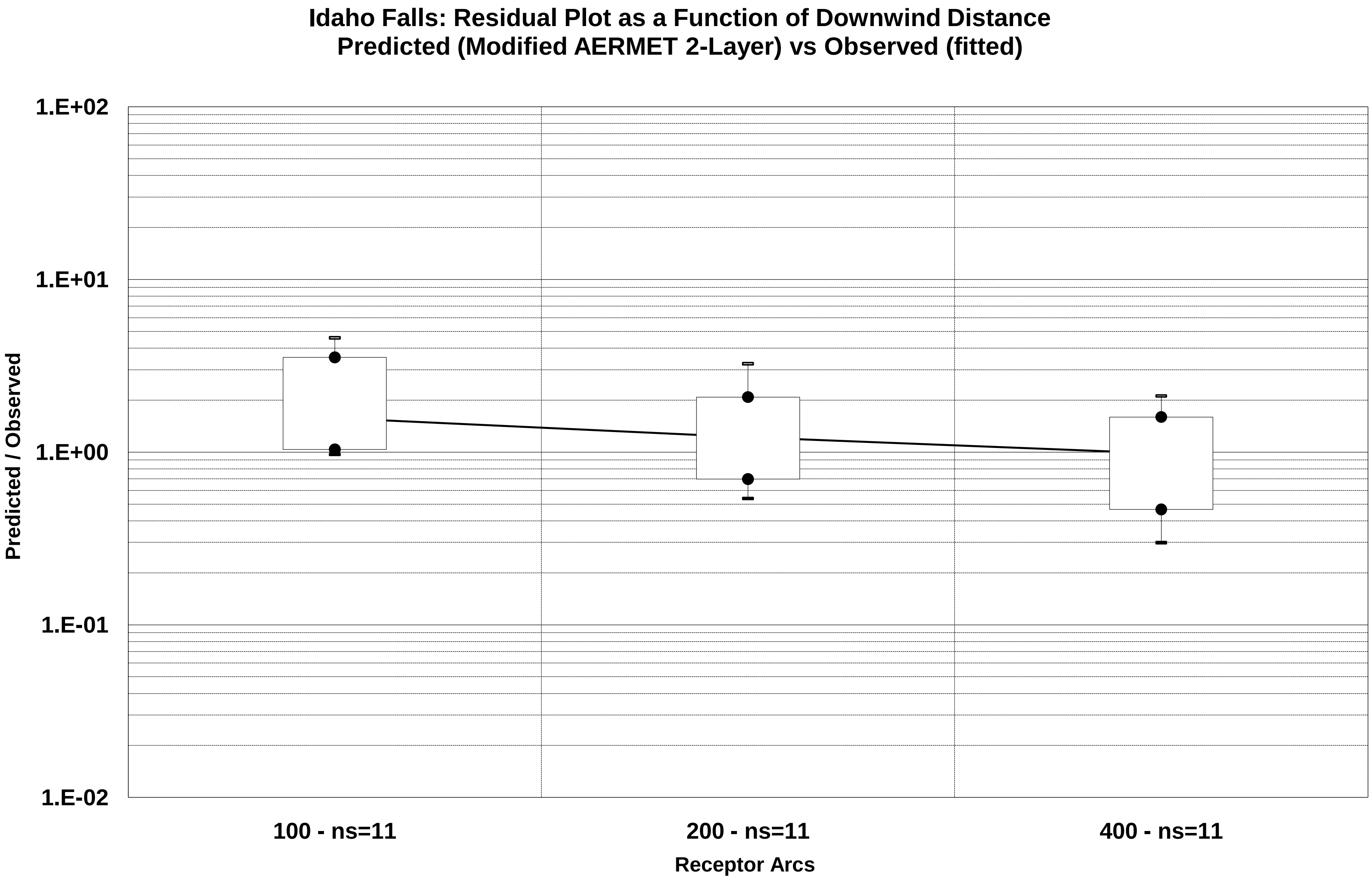


Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (AERMOD Base 2-Layer) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

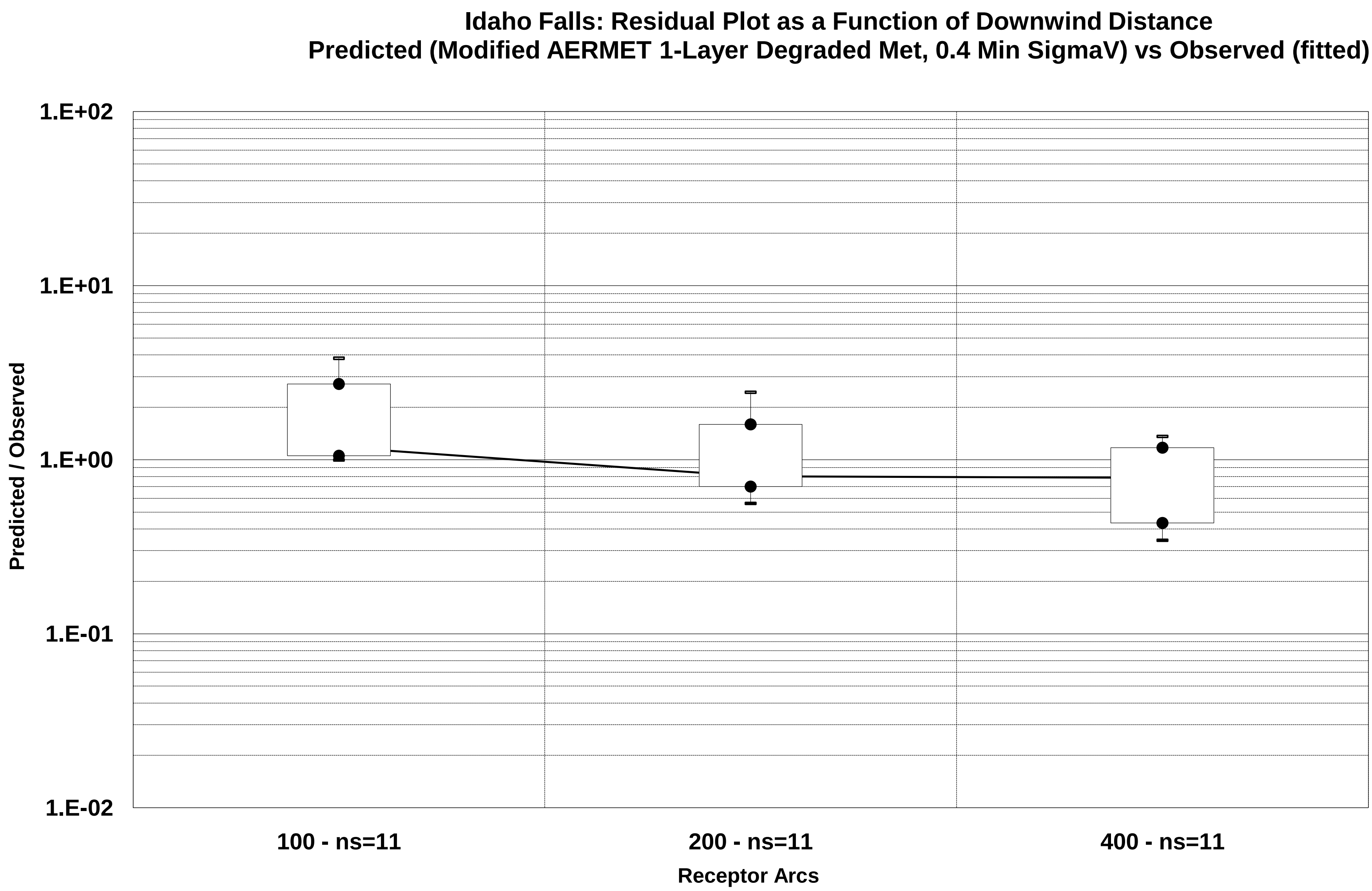

Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer Degraded Met) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

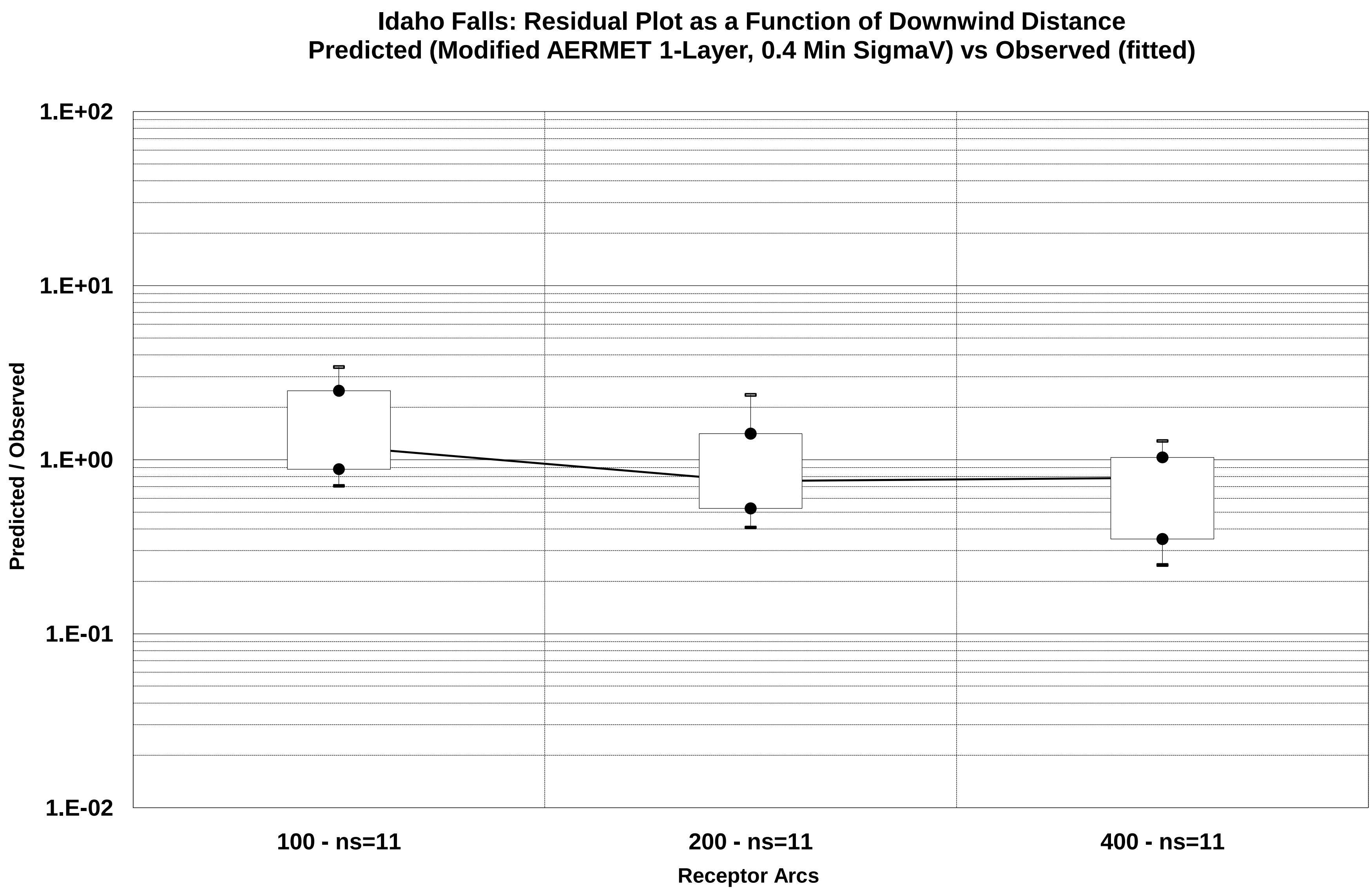
Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer) vs Observed (fitted)



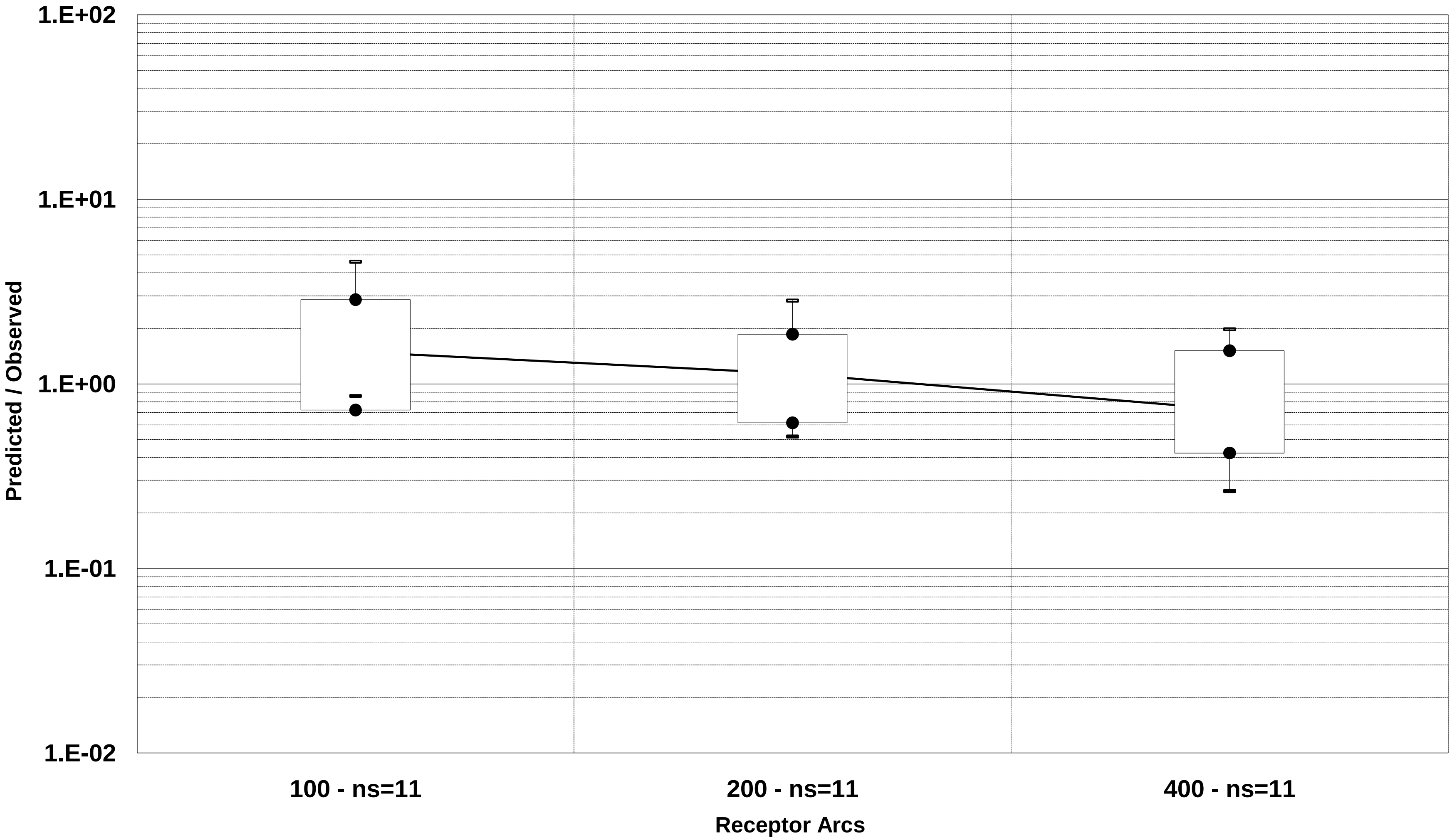


Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 2-Layer) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs


Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer Degraded Met, 0.4 Min SigmaV) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

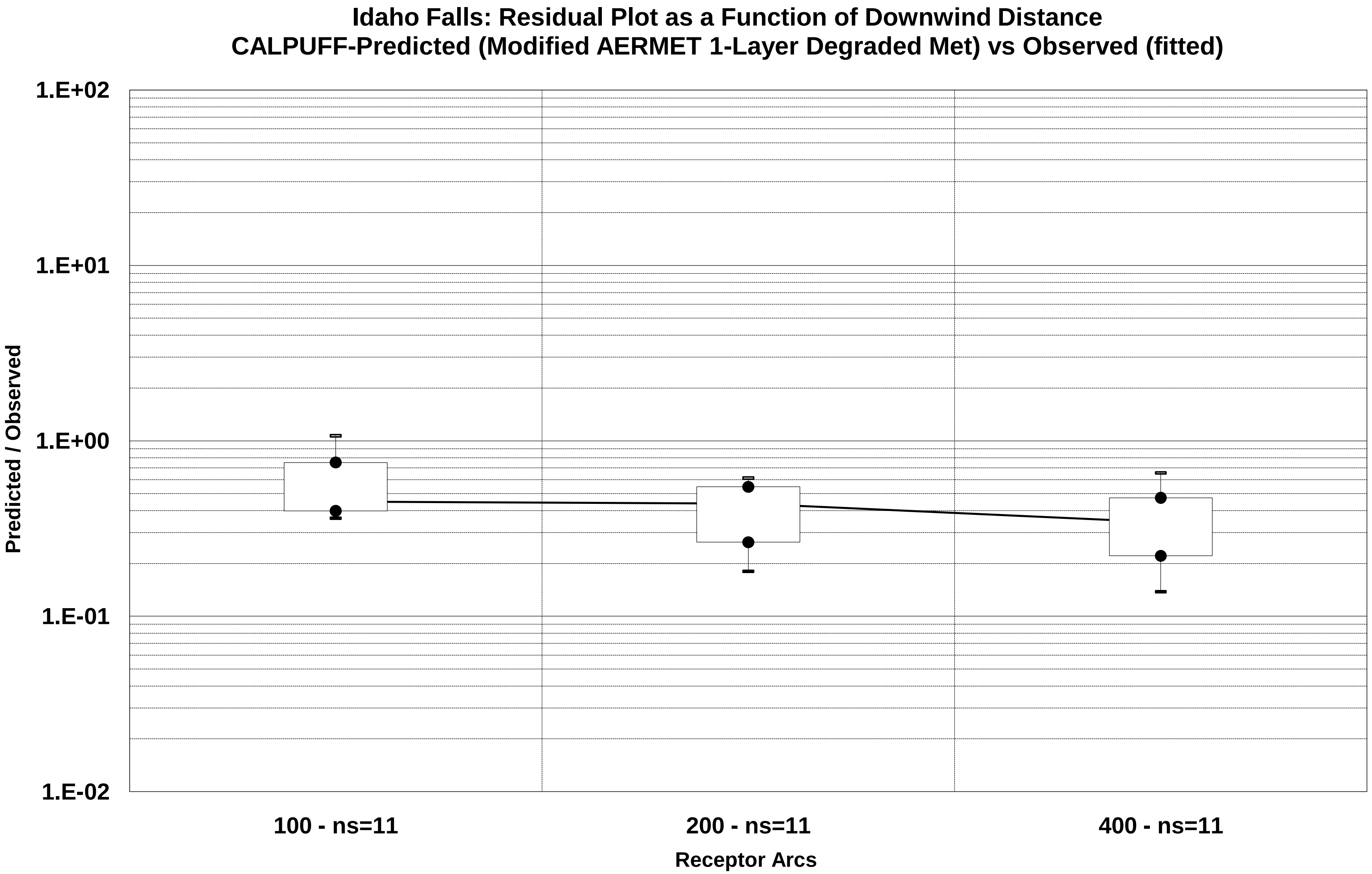

Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer, 0.4 Min SigmaV) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

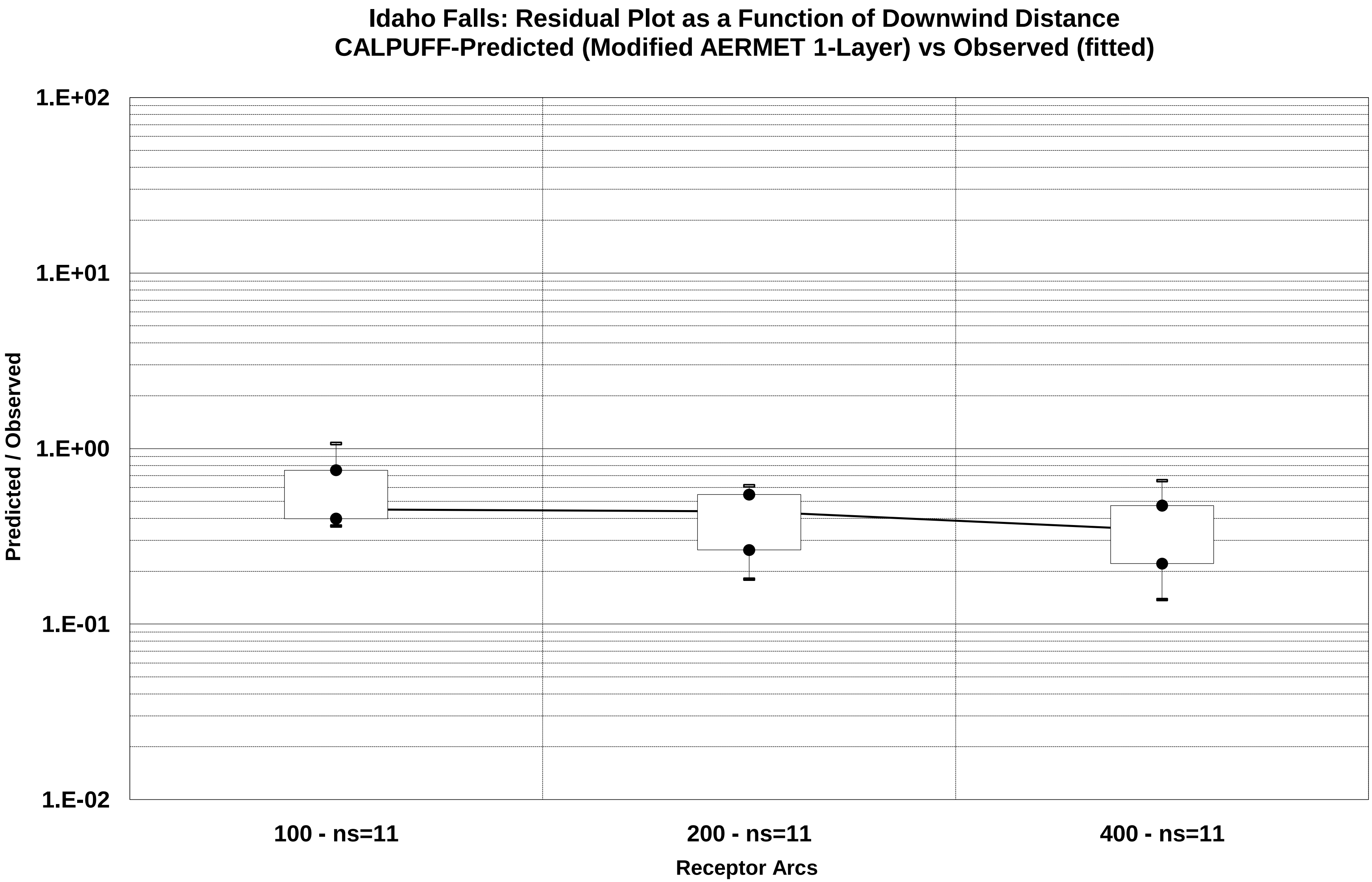
Idaho Falls: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 2-Layer, 0.4 Min SigmaV) vs Observed (fitted)

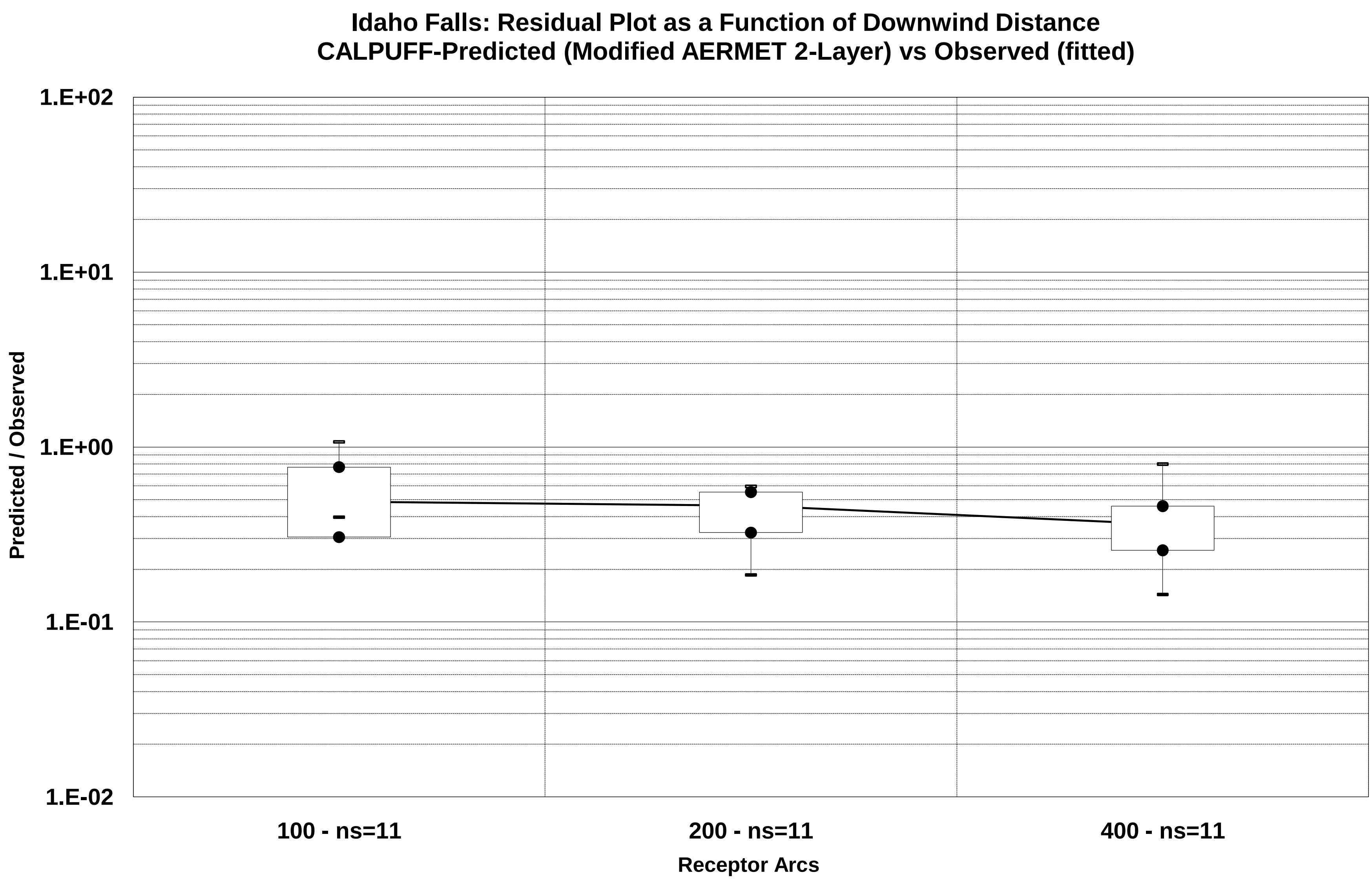


Idaho Falls Residual Plots

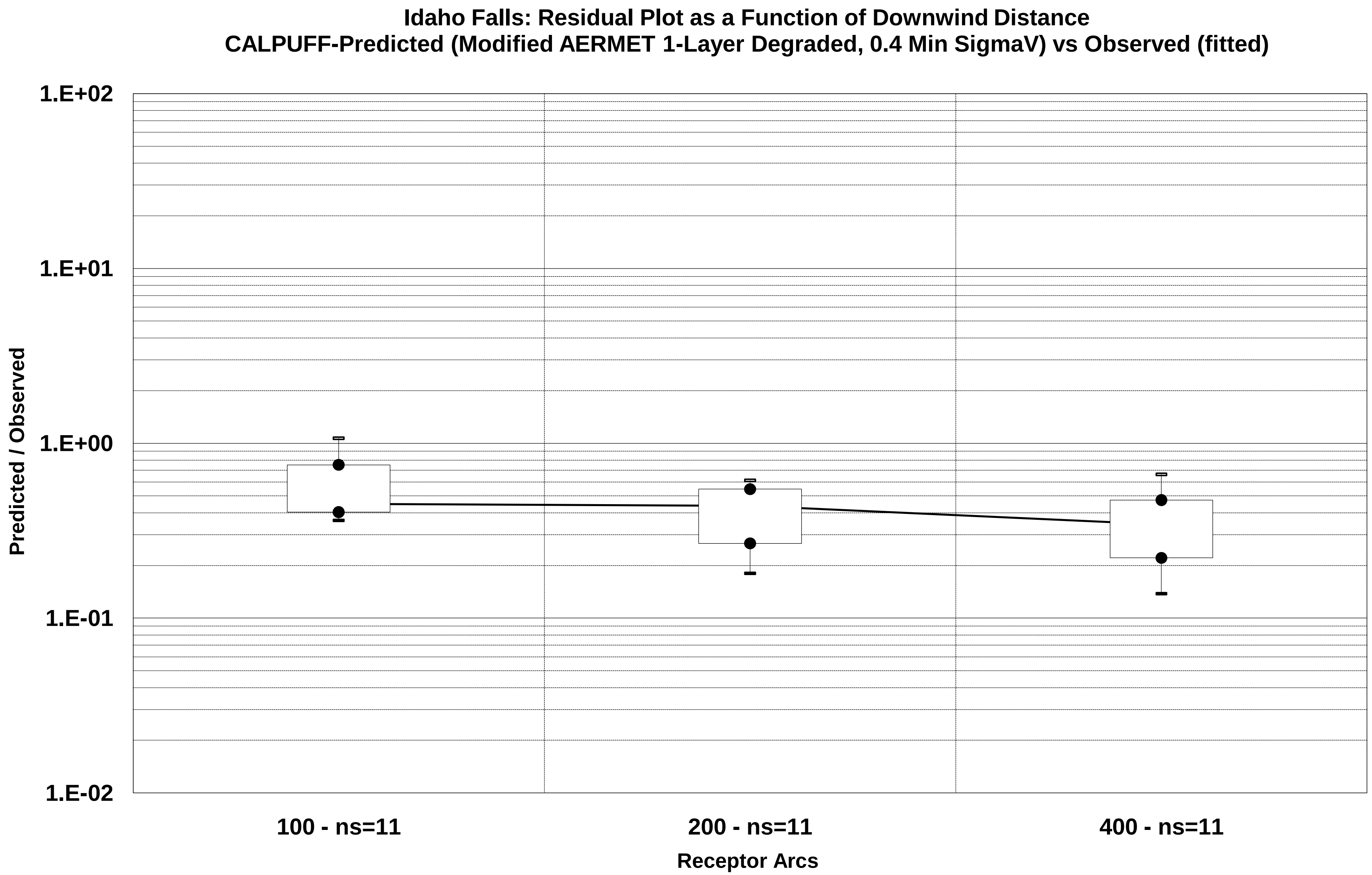
CALPUFF

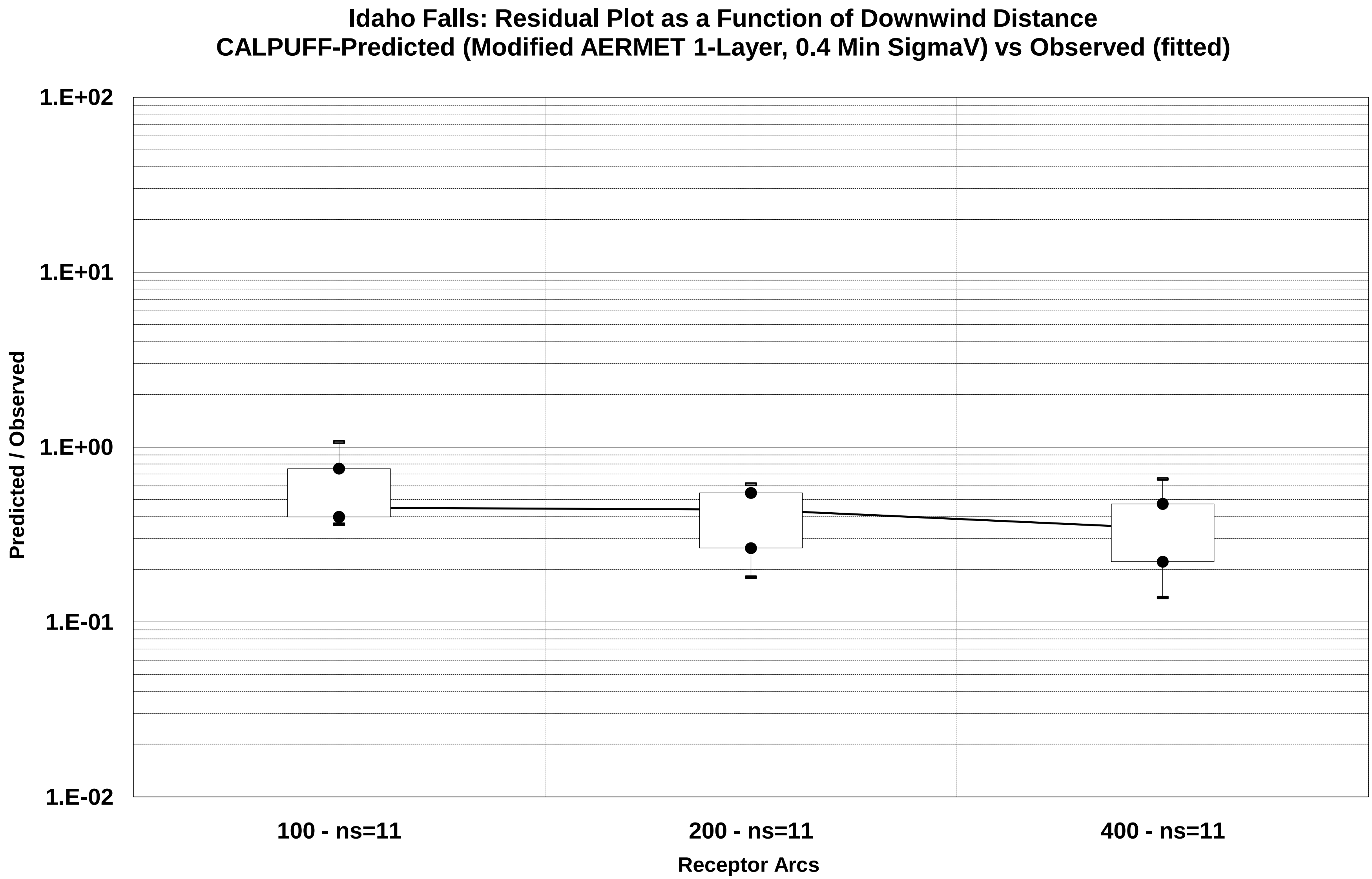

Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer Degraded Met) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs


Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

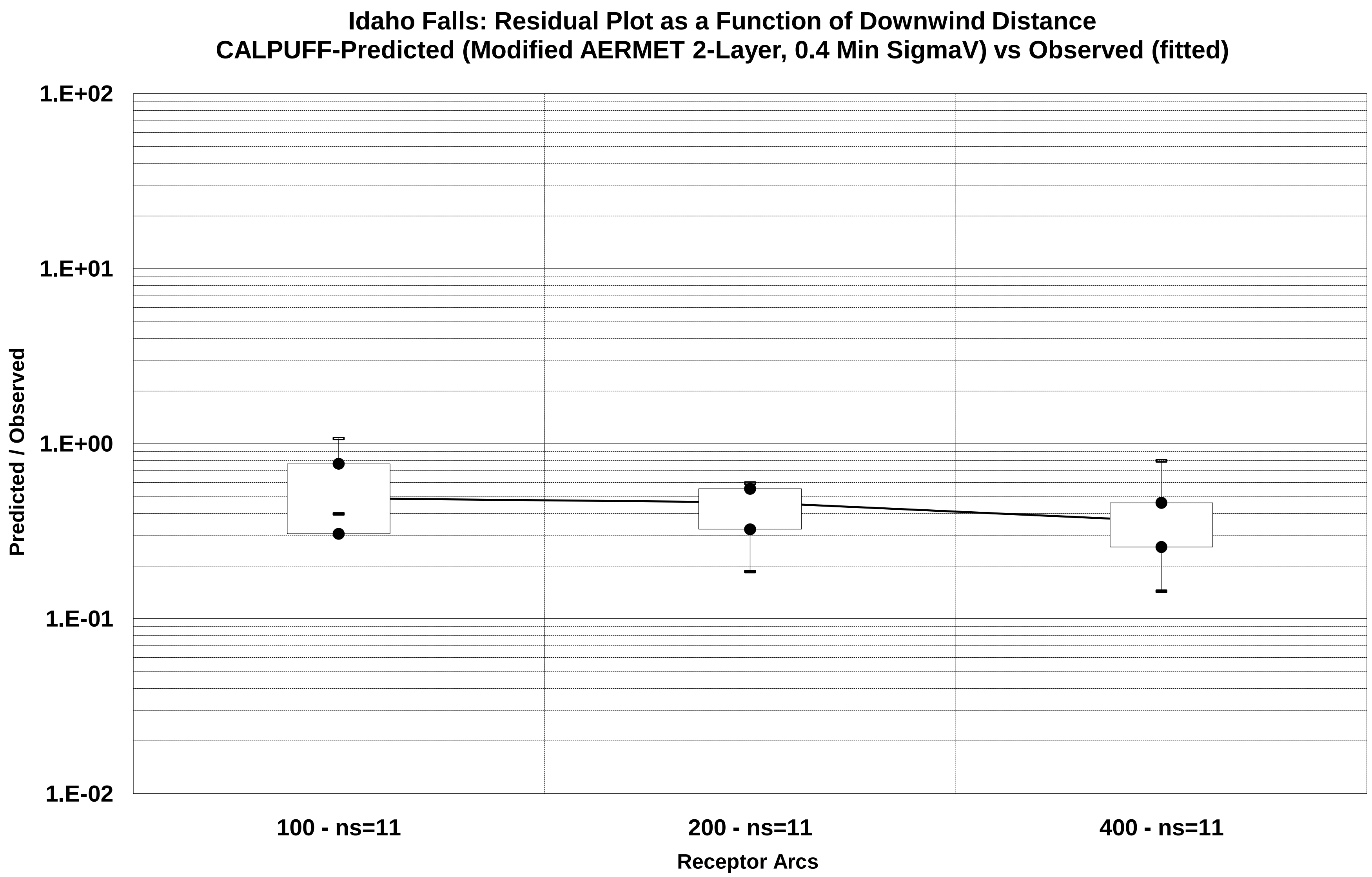


Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 2-Layer) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs


Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer Degraded, 0.4 Min SigmaV) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

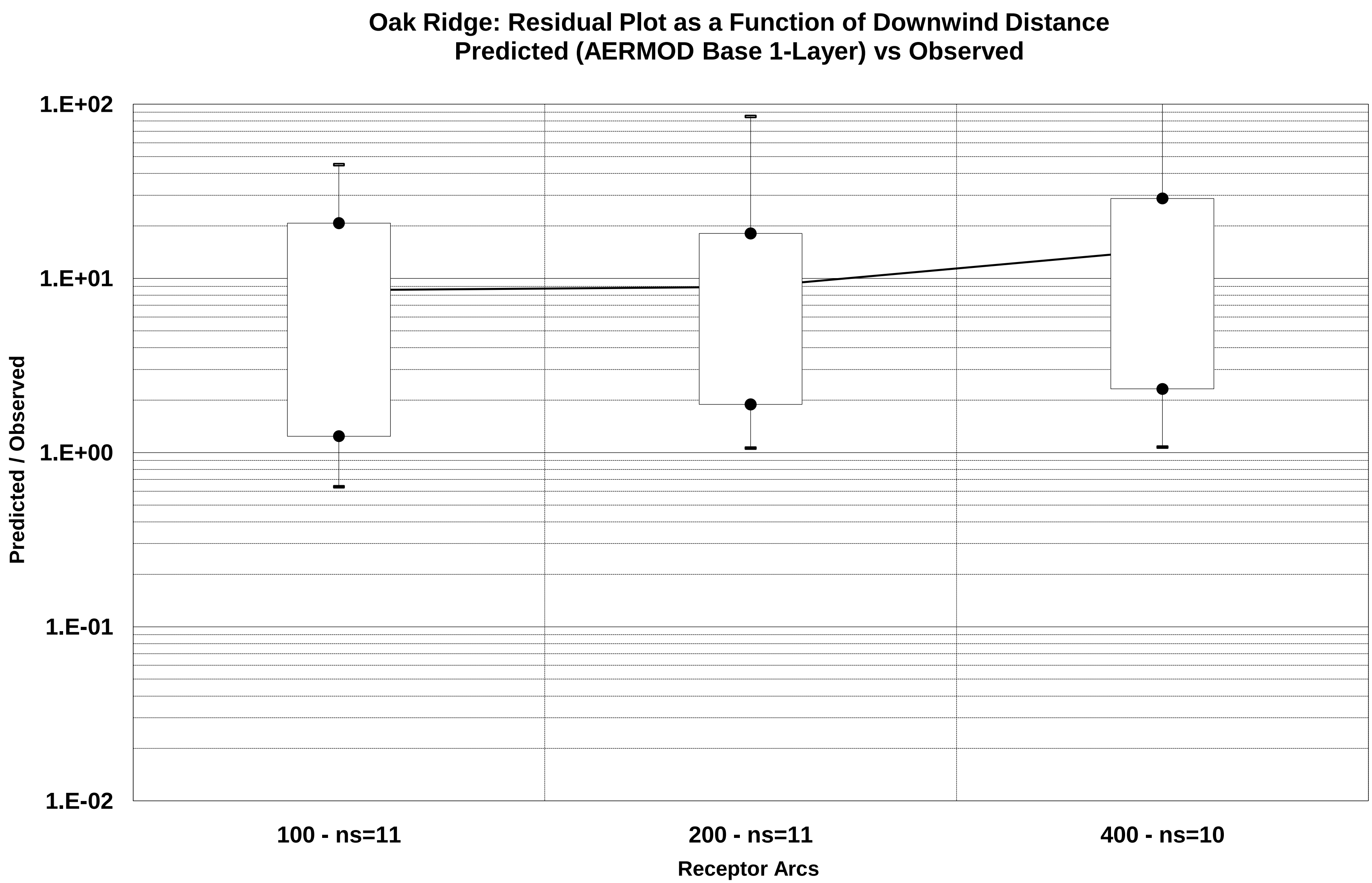


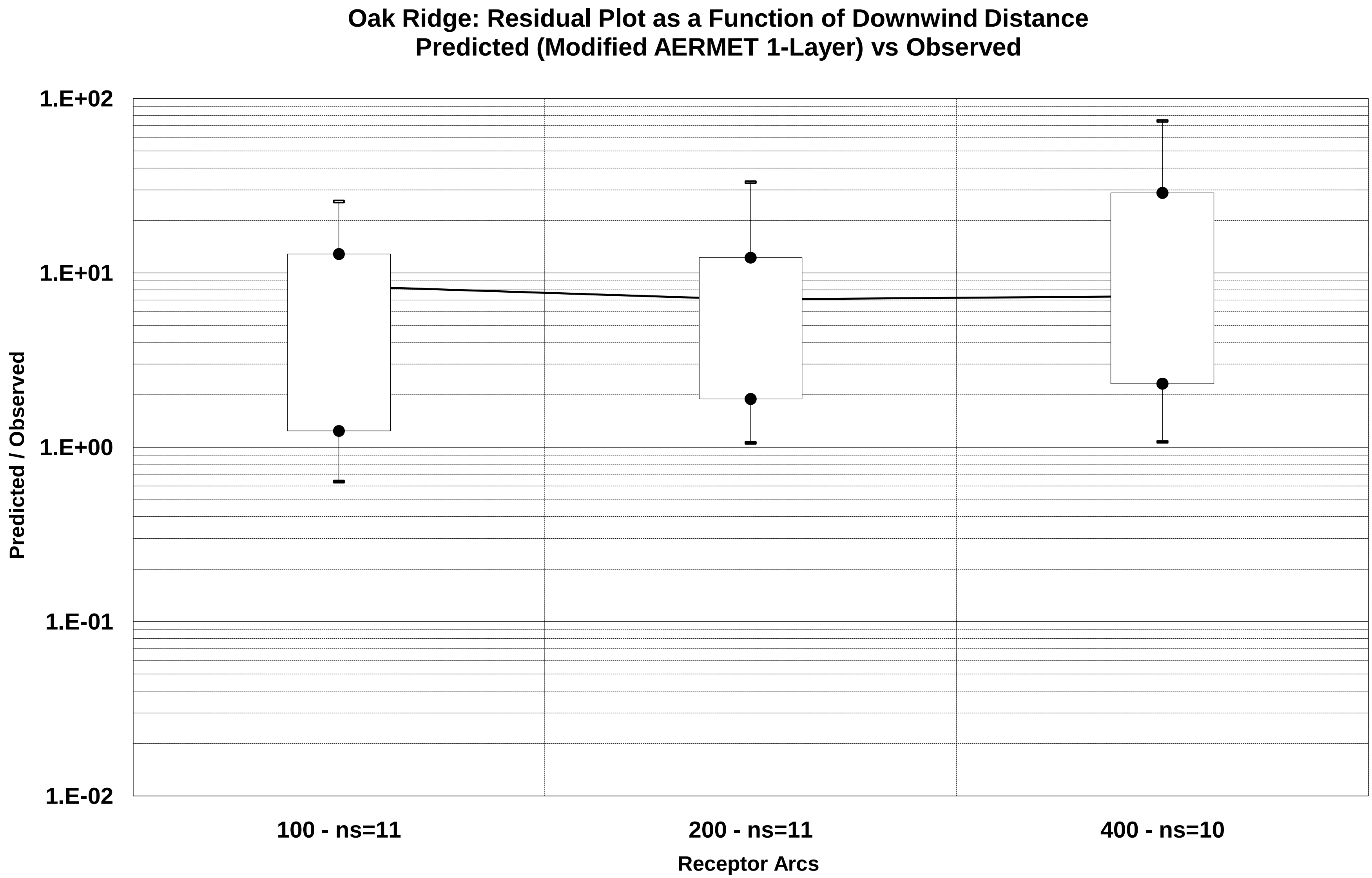
Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer, 0.4 Min SigmaV) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs


Idaho Falls: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 2-Layer, 0.4 Min SigmaV) vs Observed (fitted)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=11
Receptor Arcs

Oak Ridge Residual Plots

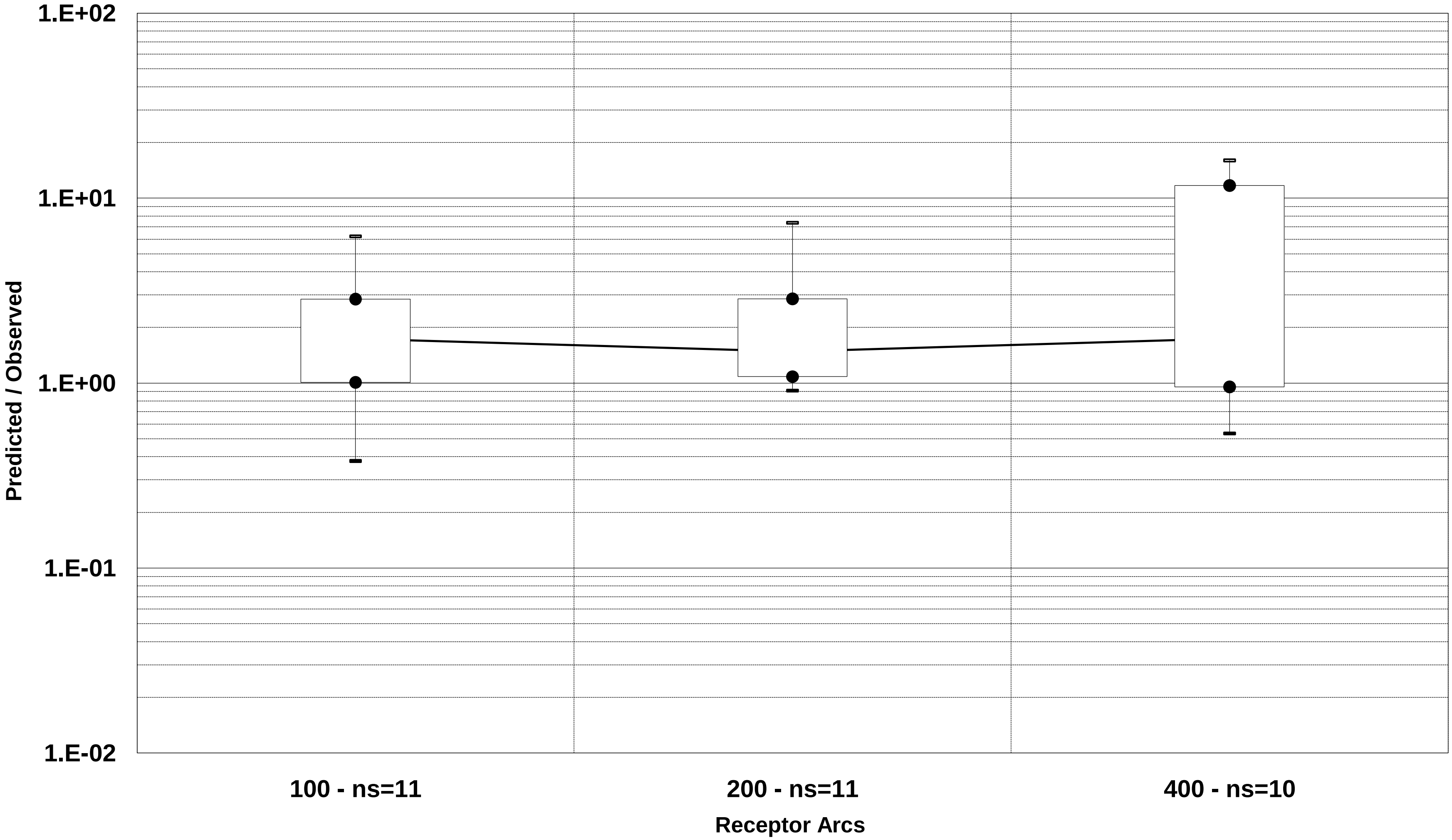
AERMOD


Oak Ridge: Residual Plot as a Function of Downwind Distance
Predicted (AERMOD Base 1-Layer) vs Observed
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=10
Receptor Arcs



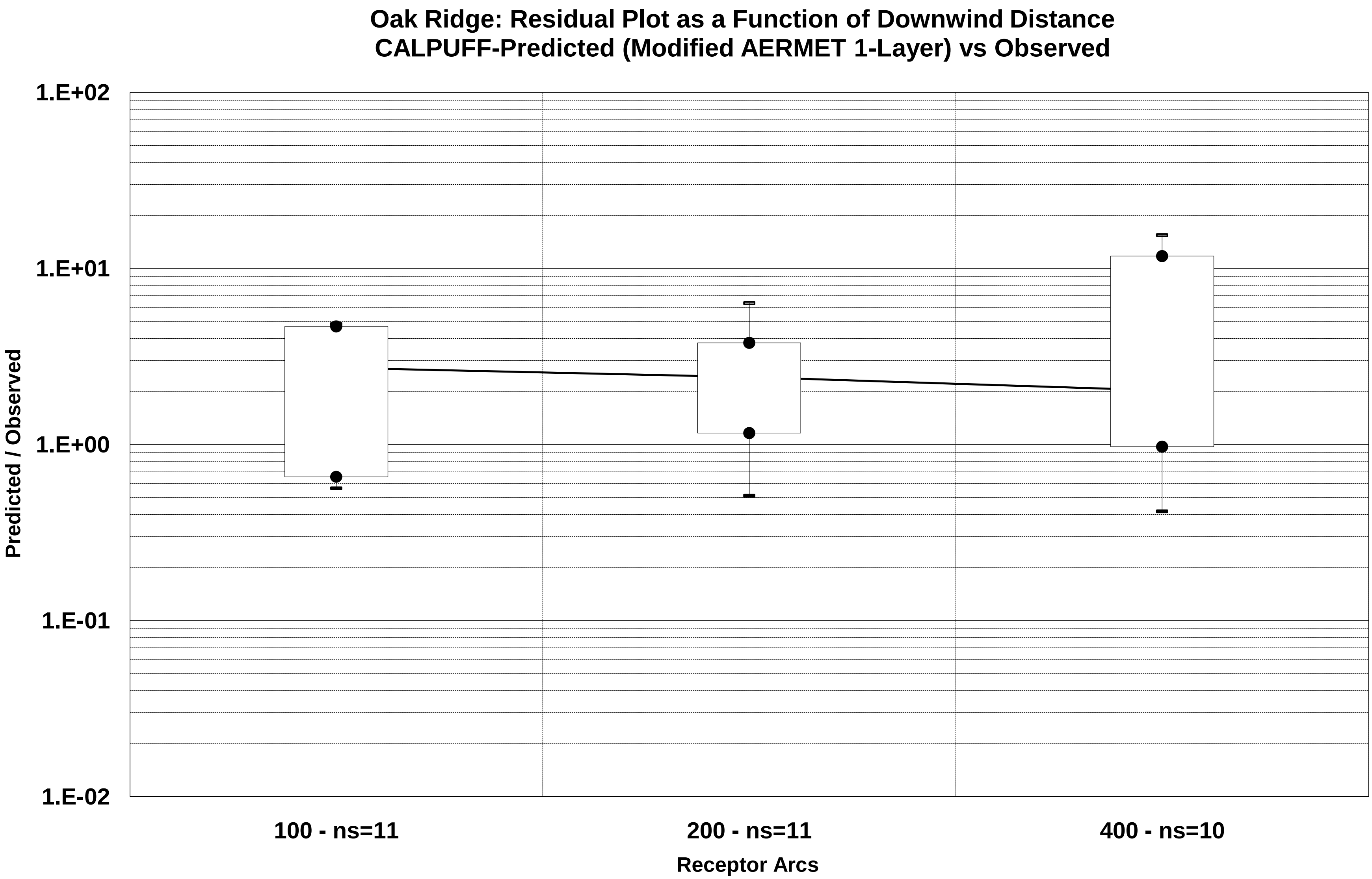
Oak Ridge: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer) vs Observed
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=10
Receptor Arcs

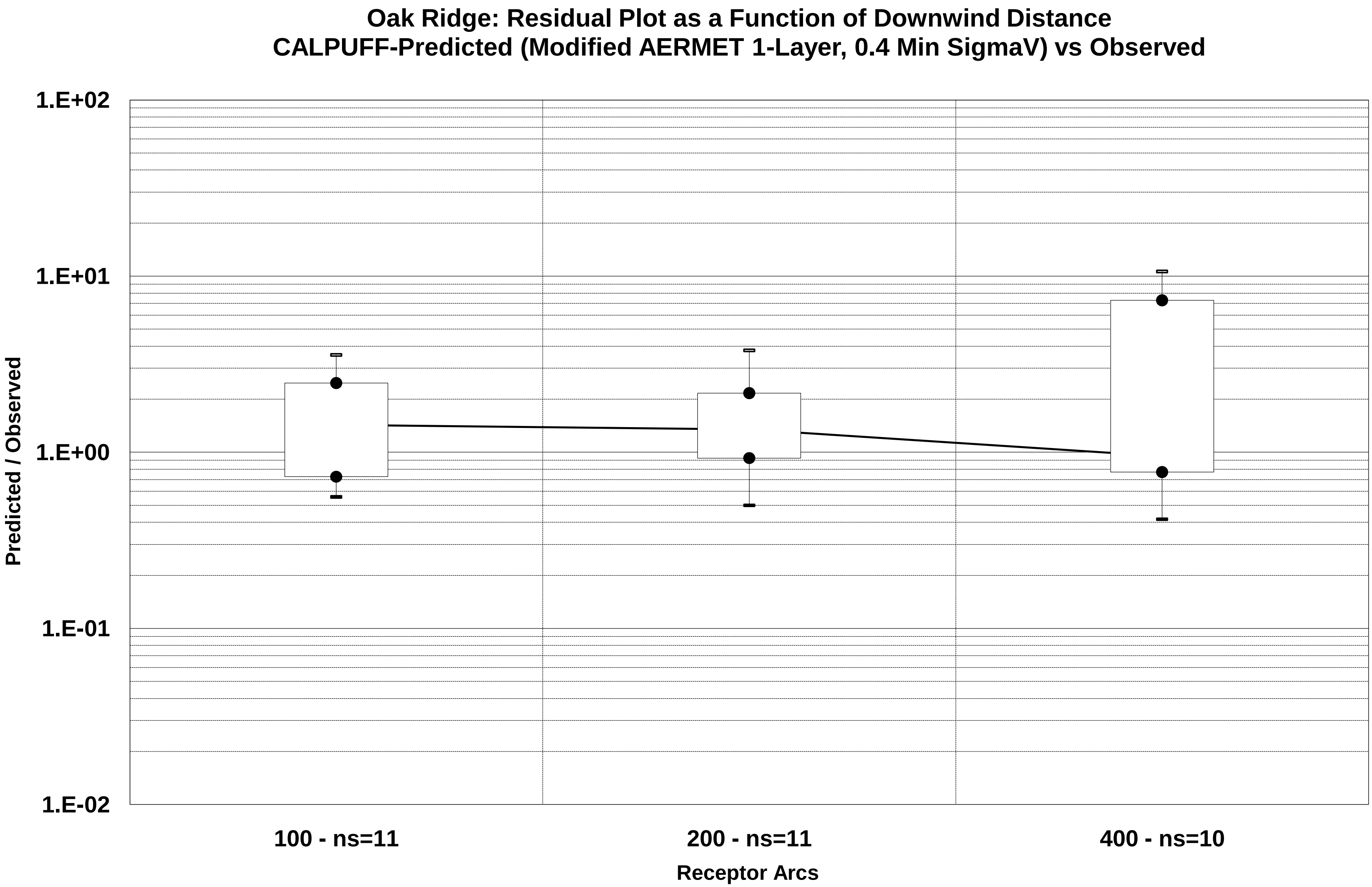
Oak Ridge: Residual Plot as a Function of Downwind Distance
Predicted (Modified AERMET 1-Layer, 0.4 Min SigmaV) vs Observed



Oak Ridge Residual Plots

CALPUFF


Oak Ridge: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer) vs Observed
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=10
Receptor Arcs


Oak Ridge: Residual Plot as a Function of Downwind Distance
CALPUFF-Predicted (Modified AERMET 1-Layer, 0.4 Min SigmaV) vs Observed
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Predicted / Observed
100 - ns=11
200 - ns=11
400 - ns=10
Receptor Arcs