Progress on Low Wind Modeling Refinements in AERMOD

A look at the AERMOD dispersion modeling system’s treatment of low wind speed conditions in light of the release of the Appendix W rule.
In 2005, the U.S. Environmental Protection Agency (EPA) promulgated a new dispersion model, the AERMOD modeling system, which replaced the Industrial Source Complex (ISC) model as the preferred model for short-range air dispersion applications. Historically with ISC, winds below 3 knots (1.5 m/sec) were reported as calm and were not modeled, since steady-state Gaussian models such as ISC and AERMOD cannot handle calm winds. As AERMOD and available wind measurements at airports have evolved since 2005, it has become routine for modeling applications to include hours with wind speed observations much lower than 1.5 m/sec. The instrumentation and recording methods for Automated Surface Observing System (ASOS) stations that are a primary source of input data to AERMOD have also evolved. Many ASOS stations are now equipped with sonic anemometers with the ability to record winds less than 0.1 m/sec. Routine use of very low wind speed observations in modeling, even with steady-state modeling limitations, has become more prevalent with the updated instrumentation and the evolution of AERMOD’s AERMINUTE tool for processing sub-hourly winds.

With these developments and increasing user experience after AERMOD was promulgated, it became evident that the more limiting low wind conditions can often lead to the highest predicted concentrations. However, the lower wind conditions were not thoroughly tested when AERMOD was developed because, as noted above, the instrumentation for measuring such low wind conditions had not been deployed at many observational stations. Efforts to conduct new low wind evaluations for AERMOD’s meteorological pre-processor (AERMET), as well as recommended refinements to the dispersion model, AERMOD, were reported in 2010 by Paine et al. EPA eventually included similar refinements in AERMET and AERMOD starting in late 2012 to account for two areas of model updates, which were proposed by EPA (80 FR 45340, July 29, 2015) for preferred guideline status.

The refinements proposed by EPA for preferred guideline status improve overall model performance of steady-state models in low wind conditions. Specifically, those refinements are as follows:

1. **A meteorological refinement (ADJ_U*)** that adjusts the computation of the friction velocity in AERMET to improve the original formulation. Friction velocity is a planetary boundary layer parameter used by AERMOD in its meteorological profiling to compute turbulence and the mixing height in stable conditions.

2. **A dispersion refinement (LOWWIND1, LOWWIND2, and most recently the EPA-proposed LOWWIND3 option)** in AERMOD that involves an increase in the minimum lateral turbulence (sigma-v) above the default 0.2 m/sec to account for additional meander not currently accounted for in the original model formulation under low wind conditions.

Both of these refinements improve the model’s characterization of dispersion in low wind conditions by accounting for the effects of meander and local-scale turbulence in low wind speed conditions.

**Low Wind Limitations for Steady-State Models**

During low wind speed (LWS) conditions, the dispersion of pollutants is limited by diminished fresh air dilution. Anfossi et al. noted that in LWS conditions, dispersion is characterized by meandering horizontal wind oscillations. Sagendorf and Dickson and Wilson et al. found that under LWS conditions, horizontal diffusion was enhanced because of the meander, and the resulting ground-level concentrations could be much lower than that predicted by steady-state Gaussian plume models that did not account for the meander effect.

A parameter that is used in the computation of the horizontal plume spread in AERMOD (which accounts for meandering in low wind conditions) is the standard deviation of the cross-wind component, \( \sigma_v \), which can be parameterized as being proportional to the friction velocity, \( u^* \) (Smedman; Mahrt). These investigators found that there was a minimum, non-zero value of \( \sigma_v \) that can be attributed to wind meandering over the course of a given hour. Hanna found that the hourly-averaged \( \sigma_v \) has a non-zero minimum value of about 0.5 m/sec as the wind speed approaches zero. Chowdhury et al. noted that a minimum \( \sigma_v \) of 0.5 m/sec is a part of the formulation for the advanced puff model SCICHEM.

The EPA-proposed AERMET ADJ_U* formulation was based upon research by Qian and Venkatram, whose upward adjustment of the friction velocity under low wind conditions

![Figure 1. Nature of recent EPA change to the ADJ_U* minimum friction velocity determination.](image-url)
was generally consistent with the suggestions of Paine et al. \(^3\)

EPA’s upward adjustments to the minimum sigma-\(v\) in the AERMOD dispersion model using the LOWWIND3 option were also consistent with discussions above involving several investigators that recommended minimum sigma-\(v\) values up to 0.5 m/sec to properly account for plume meander.

**Appendix W Low Wind Updates for AERMET**

The AERMET 16216 release in EPA’s final Appendix W rule \(^12\) significantly altered, without prior warning, the minimum \(u^*\) value from the proposal, reducing it to half of the value it had been in previous versions dating back to 2012 when it was first introduced. EPA classified this change as a “bug fix” that was discovered when they re-reviewed the discussion in the Qian and Venkatram paper regarding the minimum \(u^*\) value for the Cardington database used to establish the AERMET formulation. The previous AERMET versions had used a minimum \(u^*\) that was twice the value noted for the Cardington database in the Qian and Venkatram paper (see this illustrated in Figure 1). However, as explained below, EPA’s earlier ADJ \(_{U^*}\) implementation may be reasonably accurate.

There are several reasons why the EPA’s fix for the ADJ \(_{U^*}\) approach deserves further review and comment:

- The evaluations \(^13\) done by EPA for the previous AERMET implementation of ADJ \(_{U^*}\) showed good performance (without an under-prediction tendency with exclusion of turbulence data).
- The Qian and Venkatram study used a roughness length that is too low (0.025 m rather than values ranging up to 0.05 m as noted by Luhar et al. \(^14\)) and a temperature scale of 0.08 deg K, which can be exceeded during periods of clear skies and strong nocturnal radiation, so the minimum \(u^*\) value determined in that paper should be adjusted upward.
- In hilly terrain, there are other sources of turbulence \(^15\) that could lead to higher \(u^*\) values, such as katabatic (drainage) flows that were not present at Cardington. These factors could interfere with the simplifying assumption of the Monin–Obukhov similarity theory used in the Qian and Venkatram paper.
- It is important to keep in mind that the ADJ \(_{U^*}\) applications are most important for hilly terrain areas, not flat terrain areas.

![Figure 2](image-url). Quantile-quantile plot of the ranked 4th highest (99th percentile) daily 1-hr SO\(_2\) concentrations over all Lovett monitors using 15181 ADJ \(_{U^*}\) and LOWWIND3 (no turbulence).
Appendix W Low Wind Updates for AERMOD

Most commenters supported EPA’s proposal for the LOWWIND3 option, but the Sierra Club provided comments\(^6\) that included their evaluations of LOWWIND3 indicating an under-prediction tendency in some of the databases tested. Primarily as a result of this comment, EPA decided to keep LOWWIND3 as a “beta” option that needs a site-specific approval in its final Appendix W rule.

The specific evaluation databases selected by the Sierra Club included Baldwin, Kincaid, Lovett, Tracy, and Prairie Grass, with features noted below:

- **Baldwin (SO\(_2\))**: Rural, flat terrain, 3 184.4-m stacks, 1 full year
- **Kincaid (SO\(_2\))**: Rural, flat terrain, a 187-m stack, about 7 months
- **Lovett (SO\(_2\))**: Rural, complex terrain, a 145-m stack, 1 full year
- **Tracy (SF\(_6\))**: Rural, complex terrain, a 91-m stack height, 3 weeks
- **Prairie Grass (SO\(_2\))**: Rural, flat terrain, 0.46-m release height, several tracer release hours

The evaluation techniques selected by the Sierra Club for AERMOD were designed\(^7\) by EPA (the robust highest concentration, or RHC) in the early 1990s, and they are out of date. These procedures were developed to evaluate the ability of the model to estimate peak 1-hr average concentrations. This preceded the promulgation of statistically-based probabilistic forms of the 1-hr National Ambient Air Quality Standards (NAAQS) for SO\(_2\) and NO\(_2\) (99th and 98th percentile of the daily 1-hr maximum values per year).

The following comments are worth noting regarding the evaluation results for these databases:

- The Sierra Club (EPA docket item EPA-HQ-OAR-2015-0310-0114) showed over-predictions or unbiased results with the low wind options for Baldwin and Prairie Grass, so these databases are not being reviewed further.
- Paine et al.\(^8,9\) provided more appropriate 99th percentile statistics for Lovett (see Figure 2 that shows predicted-to-observed ratios greater than 1, vs. a 0.79 ratio reported by Sierra Club). Paine et al. also provided another full-year database (Clifty Creek) showing unbiased or over-prediction of results for that database with the use of LOWWIND3 and the previous version of the ADJ_U* algorithm (without turbulence input). These authors also noted that the Kincaid evaluation study omitted important SO\(_2\) sources that make this evaluation database unusable.
- The Tracy short-term tracer study,\(^10\) which covered only three weeks and focused only on nighttime periods, is

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not amenable to an operational evaluation study that should use a long period (i.e., a full year) of data to address a wide range of meteorological conditions. Therefore, we do not believe that reliance upon this limited database to reject adoption of LOWWIND3 leads to a valid conclusion.

Conclusion

After many years of testing and review of two low wind approaches (ADI_U* and LOWWIND3) for improvements to the AERMOD modeling system, EPA has approved a limited implementation of these needed refinements. The adjustments to the friction velocity formulation (ADI_U*) are welcome and overdue, although the late and unannounced change to reduce the minimum u_* deserves additional review and comment. EPA’s reluctance to approve a higher minimum sigma_v approach (LOWWIND3) to account for plume meander, which is recommended by several researchers, is based upon obsolete evaluation approaches that focus upon the wrong statistic (the 100th percentile concentration) for new 1-hr probabilistic forms of the U.S. ambient standard. Our evaluations with a more appropriate statistical measure indicate results that do not show model under-predictions with the previous ADI_U* and LOWWIND3 options.

Further evaluations and experiences by the modeling community will be important to continue to make progress on needed refinements to AERMOD’s treatment of low wind speed conditions as EPA considers further changes to AERMOD in the future.

Reference


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References