**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
RESEARCH TRIANGLE PARK, NC 27711

SEP 19 2017

OFFICE OF
AIR QUALITY PLANNING
AND STANDARDS

**MEMORANDUM**

SUBJECT: EPA White Papers on Planned Updates to AERMOD Modeling System

FROM: Tyler Fox, Group Leader
Air Quality Modeling Group, C439-01

TO: EPA Regional Modeling Contacts

The EPA's recent revision to the Guideline on Air Quality Modeling, also referred to as Appendix W, included enhancements to the formulation and application of the AERMOD modeling system. The final rule was published in the Federal Register on January 17, 2017, and the effective date of this action was deferred to May 22, 2017. The EPA is committed to continuing to improve the science and model performance of its preferred near-field dispersion model such that it can better inform its regulatory uses. The EPA has identified a number of planned areas for updates to the AERMOD modeling system based on areas with known science updates related to dispersion modeling and areas to address known issues or limitations in the currently available and/or applicable models for various regulatory needs. The EPA has developed white papers providing more detail that includes an overview of each issue, a literature review of active research and development, and planned paths forward on these issues. The purpose of this memorandum is to provide these white papers to the stakeholder community for discussion at the upcoming 2017 Regional/State/Local Modelers' Workshop and to gather input to inform the EPA's release of an AERMOD Development Plan in early 2018.

As attached to this memorandum, the EPA white papers cover the following areas of our planned science updates to the AERMOD modeling system:

- LOWWIND Options: Continued efforts intended to address AERMOD's tendency to overpredict in low wind conditions for some source types.
- Saturated Plumes: Effort to enhance AERMOD's treatment of moist plumes due to enhanced thermodynamics not currently accounted for by the model.

- Downwash Algorithms: Efforts to improve AERMOD predictions for downwash situations involving near-term updates and long-term incorporation of new research.
- $NO_2$ Modeling Techniques: Continued efforts intended to improve performance of AERMOD's Tier 3 methods.
- Mobile Source Modeling: Efforts intended to integrate R-LINE into the AERMOD dispersion model for future consideration as an EPA preferred model.
- Overwater Modeling: Efforts intended to allow AERMOD to replace OCD model as an EPA preferred model.

The EPA has also identified other areas below that were considered for additional research and development; however, we feel these areas need additional review and further development for consideration in future versions of the AERMOD Development Plan:

- AERMOD Modeling System: Formulation Science Issues
  - Theta* calculation method and pass through from AERMET
  - Penetrated plumes
  - Tall stacks in urban areas (boundary layer characterization)
  - Underprediction for tall stacks in flat terrain during stable hours (assess HPDM approach)
  - Complex terrain characteristics and influences
- Industrial Heat Island Effects
  - Heat islands that are not captured by populations (effective population/use of satellite data)
- Buoyant Line Sources
  - Scientific update to buoyant line source reflecting AERMOD's scientific model formulation
- Deposition
  - Particle deposition/depletion
  - Gas deposition/depletion
  - $SO_2$ half-life

The EPA also intends to pursue various updates to AERMOD-related tools and associated guidance, for example, updates to AERSURFACE, the development of a Gust Factor tool, and $NO_2$ modeling guidance for Tier 3 methods. More information will be provided on these updates as they become available.

Attachment: EPA white papers covering aforementioned planned science updates to the AERMOD modeling system

# EPA White Papers Table of Contents

OVERVIEW OF LOWWIND OPTIONS WP1-1

ISSUES RELATED TO PLUME MEANDER IN THE AERMOD SYSTEM WP1-3

MINIMUM VALUE FOR LATERAL TURBULENCE (AKA, MINIMUM $\sigma_V$) WP1-7

ISSUES RELATED TO SATURATED PLUMES IN THE AERMOD SYSTEM WP2-1

ISSUES RELATED TO BUILDING DOWNWASH IN THE AERMOD SYSTEM WP3-1

$NO_2$ MODELING TECHNIQUES WP4-1

MOBILE SOURCE DISPERSION MODELING WP5-1

OVERWATER DISPERSION MODELING WP6-1

# Overview of LOWWIND Options

## Background

In an effort to improve model predictions during low wind conditions, the EPA has developed several beta options within the AERMOD modeling system that explore various adjustments to some of the dispersion parameters in AERMOD. The first low wind options were released with version 12345 of AERMOD, which included LOWWIND1 and LOWWIND2. A third low wind option, LOWWIND3, was included in the version 15181 of AERMOD. These are each mutually exclusive, non-default beta options focused on the minimum value of $\sigma_v$ (the lateral turbulence intensity) being used in the AERMOD dispersion model, and also address the model's treatment of horizontal plume meander. A brief description of the current low wind options is provided below:

1. LOWWIND1: This option increases the default minimum $\sigma_v$ value of 0.2 m/s to 0.5 m/s, but eliminates the horizontal meander component of lateral dispersion and also eliminates upwind dispersion.

2. LOWWIND2: This option increases the default minimum $\sigma_v$ value of 0.2 m/s to 0.3 m/s, and includes an upper limit of 0.95 on FRAN, the horizontal meander component. The LOWWIND2 option includes upwind concentrations due to horizontal meander, but also includes some adjustments to the horizontal meander component, *e.g.*, a value of 12 hrs is used for the BIGT parameter (a time scale at which mean wind information at the source is no longer correlated with the location of plume material at a downwind receptor), instead of the "default" value of 24 hrs.

3. LOWWIND3 option: This option increases the default minimum $\sigma_v$ value of 0.2 m/s to 0.3 m/s, consistent with the LOWWIND1 option, but uses the non-default FASTALL approach that matches the centerline concentration for the LOWWIND2 option, based on an effective $\sigma_y$. It also eliminates upwind dispersion as being incongruous with a steady-state plume model. This may result in higher concentrations for receptors that are located "near" the plume centerline than with the LOWWIND2 option.

## LOWWIND3 and the Update to Appendix W

As part of the 2015 NPRM update to Appendix W, the EPA sought public comment on the adoption of LOWWIND3 as a preferred regulatory option in the AERMOD dispersion model. While the EPA received public comments during the rule making process that were both supportive and against the adoption, the EPA ultimately determined that there may be a possibility that the LOWWIND3 option, both alone and when combined with the ADJ_U* option, could lead to model under predictions in some cases. As a result, in the final rulemaking, the EPA decided to defer promulgating the LOWWIND3 option as a preferred regulatory option and continue to engage with the modeling community on additional research that would refine the model formulation and better address the model performance issues under low wind conditions.

## EPA white papers on LOWWIND options

To facilitate discussion on the components of the LOWWIND options and provide clarity on the state of the science of these components, the EPA has prepared two white papers detailing low wind issues:

1. Plume meander: discusses the treatment of plume meander within AERMOD and the modifications to the meander components that have been examined with previous LOWWIND options and the modifications the EPA is considering for future analysis and research, and

2. Minimum sigma-v value: discusses the minimum $\sigma_v$ parameter, which was modified in all three of the previous LOWWIND options, and the modifications the EPA is considering for future analysis and research.

These papers also present a brief review of the state of the science on each model adjustment and considerations for future updates to these potential model adjustments.

## Planned next steps with LOWWIND options within AERMOD

The combination of several adjustments to the underlying model science in a packaged "LOWWIND" option makes it difficult to isolate the impact of each adjustment on overall model predictions, and thus determine when interactions between the adjustments made in LOWWIND3 (or any other LOWWIND option) may lead to under predictions especially when used in conjunction with ADJ_U*. In order to isolate the impacts of individual adjustments and clarify the role of current and future research on addressing model performance under low wind conditions, the EPA intends to remove all three existing low wind options and replace them with a new general LOW_WIND option that allows individual adjustment of each of the relevant parameters from the original low wind options. The current plans for this new LOW_WIND model option will allow for adjustments to the following parameters[1,2]:

- **Minimum $\sigma_v$ value**. The default value in AERMOD is 0.2 m/s. LOWWIND1 used a value of 0.5 m/s, LOWWIND2 and LOWWIND3 used a value of 0.3 m/s.
- **Plume meander/Upper limit of FRAN**. The default upper limit in AERMOD is 1.0, while LOWWIND2 set this value at 0.95.
- **Minimum wind speed**. The default value in AERMOD is 0.2828 m/s, consistent with the default applied in previous versions based on SQRT(2*SVmin*SVmin) with SVmin=0.2. While this value was not adjusted in any of the LOWWIND packages, the minimum wind speed can be adjusted under the existing LOW_WIND keyword.

By separating these adjustments as individual options that may be examined individually or as a group (including the ability to recreate the original LOWWIND options), each can be studied separately and evaluated on the merit of any advancements in the state of the science around these specific parameters as well as independent evaluations of their impact on model performance. White papers on each of these options are provided as part of this package to provide the groundwork for discussion by the modeling community and to inform the research and evaluation efforts by the EPA and by external stakeholders.

---

[1] The adjustment to BIGT that was included as part of the LOWWIND2 options is currently not slated to be included in the LOW_WIND model option update but may be considered for further evaluation in future model updates, depending on the changes in available literature, EPA evaluations, or other feedback from the community.

[2] The elimination of upwind dispersion that was included as part of the LOWWIND3 option is currently not slated to be part of the LOW_WIND model option update but may be considered for further evaluation in future model updates, depending on the changes in available literature, EPA evaluations, or other feedback from the community.

# Issues Related to Plume Meander in the AERMOD System

## Overview of Issues

AERMOD accounts for plume meander (i.e., the slow lateral back and forth shifting of the plume from low frequency, non-diffusing eddies) as the plume travels downwind from the source. This is one of many formulation enhancements to dispersion over AERMOD's predecessor, the Industrial Source Complex (ISC) model. Meander decreases the likelihood of observing a coherent plume after long travel times and results in a greater plume spread and increased dispersion downwind. Currently, plume meander is only applied to point and volume sources within AERMOD and is not applied to area sources, though an area source plume is expected to exhibit similar behavior downwind of the source.

In addition, under the current default options, AERMOD has shown a tendency to overpredict in low wind conditions for some sources, especially during nighttime stable conditions. There is a need to better understand how plume meander is affected in low wind conditions and its potential influence in situations where overprediction occurs. As discussed in more detail in the next section, plume meander in AERMOD consists of two limiting components: a coherent plume and a random plume (i.e., pancake plume). The random plume results in some amount of the plume dispersed upwind of the source, whereas the coherent plume maintains the entire mass of the plume downwind of the source.

EPA first provided beta options to address model overprediction for low wind conditions within AERMOD version 12345. These beta options included:

- ADJ_U* which adjusts the surface friction velocity (u*) during stable, low wind conditions;
- LOWWIND1 which increases the minimum value of the lateral turbulence intensity (sigma-v) from the default value of 0.2 m/s to 0.5 m/s; sigma-v is used to determine the lateral plume dispersion coefficient (sigma-y); and
- LOWWIND2 which increases the minimum value of sigma-v to a value of 0.3 m/s.

A fourth beta option, LOWWIND3, was included in the release of AERMOD version 15181. LOWWIND3 also increases the minimum value of sigma-v to 0.3 m/s. In addition to modifying minimum sigma-v, LOWWIND1, LOWWIND2 and LOWWIND3 each include changes from the default implementation of plume meander that is applied when the AERMOD is run in the default regulatory mode. Meander was not a consideration in the ADJ_U* option that was promulgated as a regulatory option in the release of AERMOD version 16216r. LOWWIND1, LOWWIND2, and LOWWIND3, however, remain beta options.

With regards to the LOWWIND options and meander, LOWWIND1 turns off the horizontal meander component altogether, whereas LOWWIND2 incorporates meander with an adjustment on the default upper limit of the meander factor (FRAN) from 1.0 to 0.95. LOWWIND2 also includes an adjustment to the default time scale at which the mean wind is assumed to no longer be correlated with the location of plume material at a downwind receptor. The time scale was changed from the default value of 24 hours to 12 hours for LOWWIND2. LOWWIND3 uses the default time scale of 24 hours. LOWWIND3 includes the same adjustment to the upper limit on FRAN as used for LOWWIND2 but eliminates upwind dispersion of the plume.

EPA is focused on the following two issues related to plume meander in the AERMOD dispersion model:

1) Meander is only applied to point and volume sources such that we intend to pursue adding meander for area sources.

2) Understanding the appropriate response of the plume in low wind conditions with regard to meander and the effect meander has on concentrations in low wind conditions. The influential aspects of meander that EPA has identified to date include the upper limit of FRAN, the time scale for which there is no correlation between the location of the plume near the source and downwind of the source, the degree to which upwind dispersion should be applied or eliminated, or whether meander should be eliminated altogether.

## Current Implementation in AERMOD

AERMOD accounts for plume meander by interpolating between two concentration limits: the coherent plume limit (which assumes that the wind direction is distributed about a well-defined mean direction with variations due solely to lateral turbulence) and the random plume limit, (which assumes an equal probability of any wind direction).

For the coherent plume, the horizontal distribution function ($F_{yC}$) has the familiar Gaussian form:

$$F_{yC} = \frac{1}{\sqrt{2\pi\sigma_y}} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \textit{eq.1}$$

where $\sigma_y$ is the lateral dispersion parameter. For the random plume limit, the wind direction (and plume material) is uniformly distributed through an angle of 2π. Therefore, the horizontal distribution function $F_{yR}$ takes the simple form:

$$F_{yR} = \frac{1}{2\pi x_r} \qquad \textit{eq. 2}$$

where $x_r$ is the radial distance to the receptor. Although the form of the vertical distribution function remains unchanged for the two plumes, its magnitude is based on downwind distance for the coherent plume and radial distance for the random plume.

Once the two concentration limits ($C_{Ch}$ - coherent plume; $C_R$ - random plume) have been calculated, the total concentration for stable or convective conditions ($C_{c,s}$) is determined by interpolation. Interpolation between the coherent and random plume concentrations is accomplished by assuming that the total horizontal "energy" is distributed between the wind's mean and turbulent components. That is,

$$C_{c,s} = C_{Ch}\left(1 - \sigma_r^2/\sigma_h^2\right) + C_R\left(\sigma_r^2/\sigma_h^2\right) \qquad \textit{eq. 3}$$

where $\sigma_h{}^2$ is a measure of the total horizontal wind energy and $\sigma_r{}^2$ is a measure of the random component of the wind energy. Therefore, the ratio $\sigma_r{}^2/\sigma_h{}^2$ is an indicator of the importance of the random component and can therefore be used to weight the two concentrations as done in eq. 3.

The horizontal wind is composed of a mean component $\bar{u}$, and random components $\sigma_u$ and $\sigma_v$. Thus, a measure of the total horizontal wind "energy" (given that the along-wind and crosswind fluctuations are assumed equal i.e., $\sigma_u = \sigma_v$), can be represented as

$$\sigma_h^2 = 2\tilde{\sigma}_v^2 + \bar{u}^2 \qquad \textit{eq. 4}$$

where $\bar{u} = (\tilde{u}^2 - 2\tilde{\sigma}_v{}^2)^{1/2}$. The random energy component is initially $2\tilde{\sigma}_v{}^2$ and becomes equal to $\sigma_h{}^2$ at large travel times from the source when information on the mean wind at the source becomes irrelevant to the predictions of the plume's position. The evolution of the random component of the horizontal wind energy can be expressed as

$$\sigma_h^2 = 2\tilde{\sigma}_v^2 + \bar{u}^2(1 - \exp(-x_r/\tilde{u}T_r)) \qquad \textit{eq. 5}$$

where $T_r$ is a time scale (= 24 hrs) at which mean wind information at the source is no longer correlated with the location of plume material at a downwind receptor. Analyses involving autocorrelation of wind statistics (Brett and Tuller 1991) suggest that after a period of approximately one complete diurnal cycle, plume transport is "randomized." Equation 5 shows that at small travel times, $\sigma_r{}^2 = 2\tilde{\sigma}_v{}^2$, while at large times (or distances) $\sigma_r{}^2 = 2\tilde{\sigma}_v{}^2 + \bar{u}^2$, which is the total horizontal kinetic energy ($\sigma_h{}^2$) of the fluid. Therefore, the relative contributions of the coherent and random horizontal distribution functions (eq. 3) are based on the fraction of random energy contained in the system (i.e., $\sigma_r{}^2 / \sigma_h{}^2$).

## Summary of Current Literature or Research

### Mortarini et al., 2016

Mortarini et al. studied meander during low-wind cases from field campaigns in Italy and Brazil. Meander and non-meander cases were identified using Eularian autocorrelation functions (EAF) of the horizontal wind-velocity components and temperature. The study concluded that meander does not depend on stability; however, meander does depend on wind speed and is further influenced by the presence of buildings. The standard deviation of the horizontal wind speed is generally large during low wind conditions. The researchers demonstrate that meander and non-meander cases can be identified based on the ratio of the standard deviations of the vertical and horizontal velocity components. Non-meander cases exhibit a larger ratio than meander cases.

### Moreira et al., 2013

This work resulted in a new formulation for the parameterization of turbulence associated with meander in a shear driven stable boundary layer. The formulation is based on a relationship between turbulence and the meander period in which patterns of movement are characterized by a weighting of turbulence and meander. The formulation was tested with a Lagrangian stochastic dispersion model against field observations at the Idaho Engineering Laboratory (INEL). Results are presented which demonstrate good performance.

### Hiscox et al., 2010

Hiscox et al. used aerosol lidar measurements from the JORNADA field campaign in the New Mexico desert to study plume spread and meander. The turbulent scale was separated from the submesoscale using multiresolution decomposition, and durations of turbulent kinetic energy (TKE) stationarity and wind steadiness were used to characterize the local scale and submesoscale turbulence. The researchers found that in strong stability during weak and variable winds, horizontal plume spread was primarily from plume meander caused by submesoscale motion, and small scale turbulence had little influence. During periods of higher wind speeds and weaker stability, meander was still dominant but the ratio of the meander to small scale turbulence decreased. The study concluded that measure of wind steadiness and the turbulence stationarity are closely related and could be viable parameters to describe plume diffusion and meander in the stable boundary layer.

## Considerations for Updates in AERMOD Model System

The EPA welcomes input from the community on possible implementations of meander for area sources.

In terms of the influence of meander during low wind conditions, the EPA is currently focusing its examination on the following parameters:

1) upper limit on the meander fraction (FRAN);
2) time scale at which there is assumed to be no correlation with the location of the plume near the source and a downwind receptor; and
3) degree or existence of upwind dispersion from the random or pancake plume.

EPA expects that the use of beta options as part of future releases of AERMOD will provide the ability to adjust, at a minimum, a subset of parameters through user input for research and experimental purposes. The EPA plans to engage with the community and welcomes input that can lend additional insight on the appropriate role of plume meander, particularly under low wind conditions. The ultimate goal for the treatment of meander is a robust beta option with values of relevant parameters set that best or most appropriately reflect the role of meander in low wind conditions.

## References

Brett, A. C. and S. E. Tuller. (1991). Autocorrelation of hourly wind speed observations. Journal of Applied Meteorology*,* 30**,** 823-833.

Hiscox, A. L., Miller, D. R., and C. J. Nappo. (2010). Plume meander and dispersion in a stable boundary layer. Journal of Geophysical Research, Vol. 115, D21105. doi:10.1029/2010JD014102.

Moreira, V. S., Degrazia, G., Timm, A. U., Roberti, D. R., and S. Maldaner. (2013). Connecting Turbulence and Meandering Parameterization to Describe Passive Scalars Dispersion in Low Wind Speed Conditions. ISRN Atmospheric Sciences, Volume 2013, Article ID 738024. http://dx.doi.org/10.1155/2013/738024.

Mortarini, L., Stefanello, M., Degrazia, G., Roberti, D., Castelli, S. T., and Domenico Anfossi. (2016). Characterization of Wind Meandering in Low-Wind-Speed Conditions. Boundary-Layer Meteorology, 161:165-182. DOI 10.1007/s10546-016-0165-6.

# Minimum Value for Lateral Turbulence (aka, Minimum $\sigma_v$)

## Overview of Issue

The lateral turbulence (or the standard deviation of lateral velocity to the average wind direction), commonly referred to as $\sigma_v$, is the amount of fluctuation in the wind speed in the direction perpendicular to the mean wind and represents the turbulent flow across a plume in the boundary layer. The lateral dimension of a plume is directly correlated to the value of $\sigma_v$, with larger $\sigma_y$ values resulting in larger plumes and lower concentrations. Thus, the observed or estimated value of $\sigma_v$ has a direct impact on model predicted concentrations. The formulations to calculate $\sigma_v$ result in values of $\sigma_v$ of zero when wind speeds approach zero (i.e., low wind conditions). However, field data suggests that the minimum values of $\sigma_v$ do not approach zero. As a result, a minimum value for $\sigma_v$ has been implemented in the AERMOD dispersion model (and other dispersion models) to adhere with the observed field data.

In other words, estimates of $\sigma_v$ in low wind conditions are often too small (approaching zero), requiring a minimum value to be set. During these low wind conditions, plume volumes are inherently small, generally resulting in higher concentrations. Increasing the minimum $\sigma_v$ will result in lowering the maximum concentrations estimated for surface releases. For elevated releases, specifically when terrain considerations are important, increasing the minimum $\sigma_v$ may increase or decrease concentrations, depending on conditions. It is expected to likely lower most concentrations, though this may not correspond to the highest modeled concentrations.

## Current Implementation in AERMOD

The calculation of $\sigma_v$ in AERMOD is described in section 4.1.6 of the AERMOD Formulation and Evaluation Document. The total lateral turbulence is the sum of the mechanical ($\sigma_{vm}$) and convective ($\sigma_{vc}$) portions:

$$\sigma_{vT}^2 = \sigma_{vc}^2 + \sigma_{vm}^2$$

The mechanical turbulence at the surface is a function of the surface friction velocity ($u_*$):

$$\sigma_{vm}^2 = 3.6 * u_*^2$$

and varies linearly from the surface up to the top of the mechanically mixed layer. The convective turbulence within the mixed layer is constant and is a function of the convective velocity scale ($w_*$):

$$\sigma_{vc}^2 = 0.35 * w_*^2$$

And decreases linearly from the convective mixing height up to 0.25 $m^2/s^2$ at $1.2*z_{ic}$ (the convective mixing height). Above $1.2z_{ic}$, $s^2_{vc}$ is held constant. The default version of AERMOD sets a lower limit for the calculated $\sigma_v$ of 0.2 m/s. The lower limit of $\sigma_v$ is adjusted with the beta LOWWIND options. LOWWIND1 uses a minimum $\sigma_v$ of 0.5 m/s, and LOWWIND2 and LOWWIND3 use a minimum $\sigma_v$ of 0.3 m/s. The minimum $\sigma_v$ value is set as the SVMIN parameter in the subroutine MODOPT in the COSET.f file in the AERMOD code.

## Summary of Current Literature or Research

The lateral turbulence parameter, $\sigma_v$, has been discussed in a number of journal articles over the past few years; however, there is not a specific emphasis on demonstrating what value should be selected as the minimum $\sigma_v$.

### Hannah et al., 1985

The more current literature suggests that this paper is the basis for the default selection of the minimum $\sigma_v$ in AERMOD. Figure 3 of this paper shows observation data collected aboard a research vessel operated off the California coast from four different research cruises. The $\sigma_v$ values for this analysis were calculated as the product of the mean wind (U) and the standard deviation of the wind direction ($\sigma_\theta$). The figure shows the range of $\sigma_v$ values, with an apparent lower limit of 0.175 m/s and a mean value of 0.5 m/s.

### Luhar, 2009

This work examines the various experimental and analytical methods employed to determine $\sigma_v$ and $\sigma_u$, or the longitudinal turbulence. There is particular emphasis on the methodologies under low-wind conditions, when the accuracy of existing methods is more sensitive to the method selection. The work identifies two equations typically used to determine $\sigma_v$ from field data:

$$\sigma_v = \bar{U} * \sin \sigma_\theta$$

and

$$\sigma_v = \bar{U} * \tan \sigma_\theta$$

where $\bar{U}$ is the mean scalar wind speed and $\sigma_\theta$ is the standard deviation of horizontal wind direction fluctuations. At low wind speeds, these functions converge to:

$$\sigma_v \approx \bar{U} * \sigma_\theta$$

The paper reviews several attempts to relate measured data to derived values of $\sigma_v$, particularly for low wind conditions. The paper presents an analysis of the various parameterizations of $\sigma_v$ and $\sigma_u$ against meteorological data collected under low wind-speed, inversion conditions at the Idaho National Laboratory in south-eastern Idaho in 1974 (Sagendorf and Dickson 1974). The paper also presents an evaluation of an alternative formulation for the calculation of $\sigma_v$ and $\sigma_u$. Estimates of $\sigma_v$ are slightly improved, while estimates of $\sigma_u$ show greater improvements. Notably, the smallest observed values of $\sigma_v$ appear to be on the order of 0.05 m/s.

### Hannah and Chowdhury, 2014

This work examines several modifications evaluated with the release of AERMOD version 12345. Specifically, modifications to the estimation of $u_*$, changes to the application of the random plume (i.e., the pancake plume), and alternative values for the minimum $\sigma_v$ and $\sigma_w$, or the vertical turbulence. Of these options, the adjusted $u_*$ was adopted as a non-beta option in AERMOD version 16216r, while the changes to the so-called “pancake plume” and the alternative values of minimum $\sigma_v$ evaluated in the paper form pieces of the LOWWIND beta options in AERMOD. The model settings are compared to the equivalent settings in the SCICHEM model, a Lagrangian puff model originally developed as SCIPUFF, but currently being updated to include chemistry options. With respect to the minimum $\sigma_v$, the paper points out that SCICHEM uses a minimum $\sigma_v$ of 0.5 m/s (and a minimum $\sigma_w$ of 0.1 m/s, versus AERMOD's minimum $\sigma_w$ value of 0.02 m/s). The paper proposes that at low wind speeds, these two differences alone could result in AERMOD having concentrations 12.5 times higher than SCICHEM.

The paper also presents a model evaluation between SCICHEM, the base version of AERMOD 12345, and one version of AERMOD that applies the adjusted u* approach, a minimum $\sigma_v$ of 0.3 m/s, and modification to the application of the pancake plume for the Oak Ride and Idaho Falls field study databases. The results suggest improved model performance for the beta AERMOD options, though it is unclear which of the options have the greatest impact on performance. SCICHEM performance is similar to the beta AERMOD performance.

### Hoinaski et al., 2017

This work examines the estimates of $\sigma_v$ and resulting estimates of $\sigma_y$ in AERMOD based on two field studies in USA's Round Hill II (Cramer, 1957) and Germany's Uttenweiller (Bächlin, 2002) experiment databases. The work emphasizes the effect of the averaging time for the calculation of the meteorological model inputs and concentrations. The work does not directly address the minimum σ value, but demonstrates the sensitivity of modeled results (and modeled over-predictions) to the estimation of the $\sigma_v$ by also running AERMOD with on-site values of $\sigma_v$. The work suggests that the Lagrangian time scale might also need examination, particularly for longer travel times. It should be noted that the data from these field studies range from 30-s averaging times up to 10-min, well below the standard time step for AERMOD (1-hour).

## Considerations for Updates in Model System

As outlined above, the $\sigma_v$ value has a very direct impact on plume size and modeled concentrations. It may seem like adjusting the minimum sigma v is straightforward way to address modeled over-predictions for low wind conditions for surface releases. However, the findings in these papers show clearly that $\sigma_v$ values can be lower than the current default of 0.2 m/s. Additionally, adjusting the minimum $\sigma_v$ values may "fix" some over-predictions for surface releases, but may negatively affect modeled predictions for elevated releases. The reviewed literature points to several methods to determine the $\sigma_v$ value that should be considered rather than simply adjusting the minimum $\sigma_v$ value. The data sets analyzed are also fairly limited, which suggest more data sets should be identified or made available to investigate the issue.

## References

Bächlin, W., Rühling, A., and Lohmeyer, A. (2002). Bereitstellung von validierungs-daten für geruchsausbreitungs-modelle-naturmessungen. Baden-Württemberg, Germany.

Cramer, H. E., and F. A. Record. (1957). Field studies of atmospheric diffusion and the structure of turbulence. Am Ind Hyg Assoc Q. Taylor & Francis, 18:126–131.

Hanna, S.R. and B. Chowdhury. (2014). Minimum turbulence assumptions and u* and L estimation for dispersion models during low-wind stable conditions, Journal of the Air & Waste Management Association, 64:3, 309-321, DOI: 10.1080/10962247.2013.872709.

Hanna, S.R., L.L. Schulman, R.J. Paine, J. Pleim, and M. Baer. (1985). Development and Evaluation of the Offshore and Coastal Diffusion Model. J. Air Poll. Control Assoc., 16, 1039-1047.

Hoinaski, L., Franco, D. and Henrique de Melo Lisboa. (2017). An analysis of error propagation in AERMOD lateral dispersion using Round Hill II and Uttenweiller experiments in reduced averaging times. Environmental Technology, 38:5, 639-651, DOI: 10.1080/09593330.2016.1205672.

Luhar, A.K., Estimating Variances of Horizontal Wind Fluctuations in Stable Conditions, Boundary-Layer Meteorol (2010) 135: 301. https://doi.org/10.1007/s10546-010-9480-5.

Sagendorf, J.F., and C.R. Dickson. (1974). Diffusion under low windspeed, inversion conditions. NOAA Technical Memorandum. ERL ARL-52, Air Resources Laboratory, Idaho Falls, 89 pp.

# Issues Related to Saturated Plumes in the AERMOD System

## Overview of Issue

Recently published literature has advanced the hypothesis that wet or moist plumes are not properly characterized in AERMOD and other dispersion models. This is particularly important given the rise in the use of “wet” scrubbers at very large industrial boilers, such as electrical generation units.

Per a recent Atmospheric Environment article[1], the authors assert that…

“in many cases for moist plumes, the effect on plume rise can be significant due to heat of condensation and should be accounted for, particularly for emission sources that operate flue gas desulphurization equipment, or scrubbers, designed to remove several pollutants from combustion plumes. The scrubbing process acts to partially or fully saturate exhaust gases while minimizing any liquid “drift” emerging from the scrubber to minimize chemically erosive processes. This process acts to cool the plume relative to the unscrubbed exhaust, resulting in a reduction of plume rise. However, the moist plume exits the stack and the heat of condensation released by the liquid water particles acts to make the plume gases warmer, giving the plume additional buoyancy. Some of this buoyancy is lost as the droplets evaporate on mixing, but a net gain in plume rise is realized from the heating/cooling process. The largest net rise is realized for the situation where the ambient air itself is near saturation.”

As described in the Atmospheric Environment article, AECOM develop the “AERMOIST” source characterization preprocessor to account for this initial condensation of the plume moisture which liberates the heat of condensation as the plume exits the stack and cools in the presences of ambient air. This additional heat increases plume buoyancy during the initial rise phase and alters the downwind dispersion of the plume and alters the model predicted concentration impact in a manner consistent with enhanced dispersion and subsequently reduces some of the near-field over predictions observed with the modeling of moist plumes with AERMOD. It should be noted that the AERMOIST preprocessor is adjusting the source characteristics to indirectly alter AERMOD’s formulation to account for the enhanced thermodynamics of moist plumes.

## Current Implementation in AERMOD

AERMOD formulations are based on an essentially dry plume and does not account for any additional heat released due to condensation in the plume. So from a theoretical and physical perspective, there is merit to the hypothesis stated above, particularly with moist plumes. The approach explored with the AERMOIST preprocessor indirectly alters the AERMOD formulation to account for the thermodynamic differences related to moist versus dry plumes and demonstrated model performance improvements in a few cases. EPA believes a direct update to the AERMOD model formulation to account for the enhanced thermodynamics associated with moist plumes would provide a more appropriate and scientifically defensible long-term path forward to address this issue.

## Summary of Current Literature or Research

The AERMOIST tool is documented in the aforementioned Atmospheric Environment article, which includes references to other peer reviewed publications that support assumptions and aspects of the

---

[1] Robert Paine, Laura L. Warren, and Gary E. Moore. Source characterization refinements for routine modeling applications. Atmospheric Environment, Volume 129, March 2016, Pages 55-67.

characterization incorporated into the AERMOIST preprocessor. At this time, there is very limited information available for supporting the scientific basis and additional AERMOD model performance evaluation based on the application of the AERMOIST preprocessor. As detailed below, there have been limited situations in which EPA regional modelers have evaluated specific applications of the AERMOIST preprocessor. Additionally, there is no known AERMOD model formulation research or development specific to moist plumes.

## Paine et al., 2016

AERMOIST is based on a moist "plume rise" model, IBJpluris, that has been evaluated with aircraft measurements of moist plumes in the peer-reviewed literature. AERMOIST uses IBJpluris to determine hourly adjustments in plume rise and then modifies stack temperatures for input to the dry plume rise model in AERMOD to force simulation of increased plume rise. The AERMOIST model modifies CEM measured data prior to input to the AERMOD system.

As presented in the aforementioned Atmospheric Environment journal article…

> "A validated, moist plume rise model called "IBJpluris" has been found to accurately predict the final rise of a moist plume (Janicke and Janicke. "A three-dimensional plume rise model for dry and wet plumes." Atmos. Environ., 2001.) and can be used to complement the dispersion modeling process when moisture content can be a significant factor. The IBJpluris model formulation includes a general solution for bent-over moist (initially saturated) chimney plumes (Janicke and Janicke, 2001). The model was reviewed by Presotto et al. (Presotto, Bellasia, and Bianconi, 'Assessment of the visibility impact of a plume emitted by a desulphuration plant.' Atmos. Environ., 2005.), which indicated that despite a number of entrainment formulas available, IBJpluris possessed the physical capability of representing the impacts of heat of condensation on symmetric chimney plume rise. The Presotto et al. (2005) paper also reported field evaluation results for the IBJpluris model involving aircraft measurements through moist plumes emitted by stacks and cooling towers. Therefore, IBJpluris was selected as the core model for developing and applying a simple adjustment method to the standard Briggs (1975) plume rise formula used by AERMOD to account for thermodynamic modification of plume rise…
>
> …This is done by performing IBJpluris model runs for both the actual moist plume and a dry plume so that the adjustments for the difference can be made and transferred to hourly plume input data for models such as AERMOD. By assuming the ambient environment that the plume rises through is identical for both a dry and wet plume, a reasonable assumption is that the ratio of the wet to dry plume rise for IBJpluris can be used to adjust the dry dispersion model plume rise to a moist plume rise prediction. The approach assumes that this scaling ratio is independent from changes in wind speed and stability, although the variations in rise may be rather large. This assumption is reasonable since the rise is functionally related to the sum of exiting buoyancy and vertical momentum fluxes and the difference between dry and moist rise depends mainly on buoyancy, which is primarily temperature- and relative humidity-dependent…
>
> …In AERMOIST, the IBJpluris model is exercised in both dry and wet mode for each range and an array of temperatures and humidity over the range of possible values, β(Ti,RHj) ratios, is

> saved for each stack that is modeled and are used to estimate the model adjustment coefficients. The β(Ta,RHa) are used to estimate the equivalent hourly plume temperatures for input to the dispersion model for each hour of emissions. By modifying only the plume temperature, multiple sources can be included in the model run, each with their own series of equivalent hourly plume temperatures. Dry plumes can also be modeled with standard, constant input data."

The Atmospheric Environmental journal article did not offer any model performance evaluation of AERMOIST. It only offered an example on a typical saturated, scrubbed power plant to demonstrate the impact on plume temperature and downwind plume height. In this sensitivity analysis, there was a 15K rise in plume temperature and then between 10 and 15% increase of plume height at 2000m downwind based on a relatively dry or moist ambient environment.

## Application of AERMOIST in Region 3 and 6 $SO_2$ Modeling Situations

Both Regions 3 and 6 have evaluated the application of AERMOIST for $SO_2$ related modeling situations in their respective Regions. In both evaluations AERMOIST has had both anticipated and somewhat unexpected results that leave a level of concern on the broad application of AERMOIST without a further and more comprehensive model performance evaluation of the AERMOIST preprocessor.

In the Region 3 case, the Brandon Shores power plant was modeled with and without AERMOIST. AERMOIST was found to have an average temperature adjustment to the plume temperature of 10 to 20 K, which is reasonable on the surface. However, there was also a percentage of adjustments exceeding 50 K with a maximum adjustment of 72 K. Raising the plume temperatures in AERMOD via AERMOIST appeared to generally raise the height of the maximum model concentration (surrogate for plume height) under stable conditions though it was not uniform. The height increase was in the 10 to 15 % range. AERMOIST appeared to have little impact on plume height during unstable (mixing) conditions. It was found through the Brandon Shore evaluation by Region 3 that the application of AERMOIST also appeared to lower the overall maximum model concentrations within the raised plume. So, there is possible more going on in the adjustments than displacing the plume.

In the Region 6 case, the Martin Lake power plant was modeled with and without AERMOIST along with another preprocessor, AERLIFT. In the Martin Lake evaluation, similar impacts of plume temperature increases in the 15 K range were noted. Also, more robust or extreme adjustments were noted of just over 100 K in several instances. Overall, there was on the order of a 15% increase in buoyancy of the plume from just the AERMOIST adjustment, which was very similar to that of the Brandon Shores case. Complicating the Martin Lake evaluation was the application of AERLIFT that had much more dramatic temperature adjustments to the plume, on the order of 200 K in some instances. When combined the two preprocessor had maximum impacts of approximately 300 K, which is completely unrealistic.

## Considerations for Updates in Model

An appropriate adjustment to the plume temperature is theoretically plausible to account for enhanced plume velocity due to the thermodynamics of wet or moist plumes when modeled with the AERMOD Modeling System. AERMOIST is based on peer reviewed literature that has some basis in making the appropriate adjustment, albeit indirectly.

The limited sensitivity analysis in the AECOM journal article and the evaluations in Region 3 and 6 demonstrate an average plume temperature adjustment of 10 to 20 K and plume height increase of approximately 15%. However, the Region 3 and 6 evaluations have presented situations where the adjustment to plume temperature has been between 50 and 100 K in some limited cases, which is a significant temperature adjustment that deviates from the Atmospheric Environment article and associated references. Region 3 found indications that the downwind modeled concentrations may have been lowered within the raised plume. Additional investigation is necessary to better understand the impacts of the AERMOIST preprocessor on modeled concentrations within the moist plume and not just at specific ground receptor locations nearby to the source in question. Region 6 has also stated that when the liquid water evaporates downwind in the plume, it reduces the buoyancy of the plume by the same amount of the initial increase. This reduction should then act to depress plume rise, but it is theorized to occur when the plume is more dilute and may have approached reached final rise – thus minimizing the effect. Both Region 3 and 6, as well as OAQPS, have expressed some concern about the use of relative humidity levels at typical observation (2m) height to be representative of relative humidity levels of the ambient air at stack height (often 100m to 200m).

As a result of the EPA regional office findings, EPA believes that there are outstanding questions about the broad application of the current AERMOIST source characterization preprocessor without a comprehensive model performance evaluation of AERMOD with AERMOIST for a variety of sources and locations, *e.g.*, flat and complex terrain. Ideally, this comprehensive model performance evaluation would be included in a subsequent peer-review journal article(s). Additionally, both of the cited journal articles in the Atmospheric Environment article (Janicke and Janicke, 2001 and Presotto et al., 2005), as presented above, need further review and consideration for potential future AERMOD formulation enhancements to directly account for the different dispersion characteristics of moist plumes.

## References

Paine, R., Warren, L., and Gary E. Moore. (2016). Source characterization refinements for routine modeling applications. Atmospheric Environment, Volume 129, March 2016, Pages 55-67.

Janicke, U. and L. Janicke. (2001). A three-dimensional plume rise model for dry and wet plumes. Atmospheric Environment, Volume 35 (5), Pages 887–890.

Presotto, L., Bellasia, R., and R. Bianconi. (2005). Assessment of the visibility impact of a plume emitted by a desulphuration plant. Atmospheric Environment, Volume 39 (4), Pages 719-737.

# Issues Related to Building Downwash in the AERMOD System

## Overview of Issues

Buildings and similar structures in the path of air flow create a turbulent wake region on the leeward (i.e., downwind) side of the building. A plume caught in the path of this flow is drawn into the wake, temporarily trapping it in a recirculating cavity. This downwash effect leads to higher ground-level pollutant concentrations near the building than if the building was not present. Building downwash is accounted for in the AERMOD modeling system using the Plume Rise Model Enhancements (PRIME) model; however, the PRIME algorithms, as they were originally implemented in AERMOD, have not been updated since the promulgation of AERMOD in 2005. The current implementation for treating downwash does not reflect more recent research and the current understanding of downwash effects. With more stringent National Ambient Air Quality Standards (NAAQS) in place, such as the 1-hour $SO_2$ and $NO_2$ standards with which facilities must comply, there has been an increased focus on the need to improve AERMOD's performance in modeling building downwash.

Analyses have shown AERMOD to both overpredict and underpredict ground-level concentrations in the building wake, depending on the building dimensions; stack height; stack location; and the orientation of the building relative to the wind direction. Overprediction and underprediction have been demonstrated in analyses of single, one-tiered rectangular buildings. Some examples in which AERMOD has been shown to be deficient with regard to building downwash include elongated buildings, buildings that are angled rather than perpendicular to the wind, and buildings with stacks located near a building corner (Perry et al., 2016).

Building configurations at many facilities are far more complex than a single one-tiered building. A site may contain multiple buildings having multiple tiers at different heights, all contributing to downwash for a single stack. AERMOD, however, can only model the equivalent of a single building or tier. The building preprocessor, BPIPPRM, analyzes the building and tier dimensions relative to the height and distance of each emission release. BPIPPRM identifies a single influencing building/tier specific, by wind direction, for each emission release point and prepares the required input parameters for AERMOD. This simplification of a complex building configuration to a single one-tiered structure can be inadequate to sufficiently model building downwash for many facilities.

Further, the building downwash algorithms in AERMOD are based on solid, square and rectangular ground-based buildings. Porous and lattice-type structures that are common at many sites have been shown to have an influence on flow and dispersion in different ways than solid buildings. Currently, these types of structures can only be modeled in AERMOD as solid buildings which are not representative of these structures.

## Current Implementation in AERMOD

The treatment of downwash in AERMOD is based on the PRIME model which is integrated into AERMOD for point sources (Schulman et al. 2000). The development of the PRIME model was sponsored by the Electric Power Research Institute (EPRI) with a focus on: 1) enhanced plume dispersion coefficients from the turbulent wake, and 2) reduced plume rise that results from descending streamlines in the lee of the building and increased entrainment in the wake (EPRI, 1997).

AERMOD requires building dimensions, including along-wind building length (BUILDLEN), across-wind building width (BUILDWID), and building height (BUILDHGT) for 36 wind flow vectors, every 10 degrees, relative to each stack. As already mentioned, the building dimensions for the influencing tier for each stack and flow vector are determined by the preprocessor BPIPPRM. The PRIME model assumes the wind is always perpendicular to the building face. For each of the 36 wind flow vectors, BPIPPRM derives effective building dimensions for a rectangular building perpendicular to the wind using the projected building length and width for the respective BUILDLEN and BUILDWID parameters. The projected length and width are the along-flow and across flow distances across the footprint of the angled building, respectively. Two additional data requirements computed by BPIPPRM are the along-flow (XBADJ) and across-flow (YBADJ) distances from the stack to the center of the upwind face of the projected building, for each of the 36 wind flow vectors.

A stack is evaluated by BPIPPRM to determine if it is affected by building downwash based on Good Engineering Practice (GEP) stack height and the 5L area of influence, where L is the lessor of the building height and projected building width. For multi-tiered buildings, each tier is treated like a separate stand-alone structure. The input parameters required by AERMOD are then derived for the direction-specific controlling tier.

The PRIME model reduces plume rise based on streamline deflection near the building, vertical wind speed shear, enhanced dilution from the turbulent wake and velocity deficit. Plume mass is partitioned between two wake regions: a near-wake cavity of recirculating mass adjacent to the building and a far-wake with enhanced dispersion. Dispersion of the recirculated cavity mass is based on building geometry and is assumed to be uniformly mixed. Mass is re-emitted from the cavity into the far-wake region at the boundary of the cavity and combined with the portion of the plume that was not drawn into the cavity. The rate of dispersion in the far-wake region is based on source location, release height, and building geometry. Dispersion in the near-wake is determined using a probability density function, while dispersion in the far-wake is based on an eddy diffusivity model. Beyond the wake, the total concentration at a point is based on a weighting of the concentration computed by PRIME and the concentration computed by AERMOD (i.e., assuming no downwash). The weighting parameter decreases exponentially with vertical, lateral and downwind distance from the wake.

## Summary of Current Literature or Research

The peer reviewed, published research has primarily focused on the evaluation of AERMOD/PRIME performance based on wind tunnel studies of simple, rectangular, ground-based, solid structures.

### Olesen, et al., 2009

AERMOD/PRIME and the Danish *Operationelle Meteorologiske Luftkvalitetsmodeller*[1] (OML) model were evaluated against a past wind tunnel database (Thompson, 1993). Four case studies were presented, based on the combinations of stack height at building height and 1.5 times the building height for a cubic building and a building with a width four times the height. The stack was located in the center of the building and wind flow was perpendicular to the building for each case. The wind tunnel data show that there is little sensitivity to building width for stacks at building height; however, this reverses with stacks at 1.5 times the building height. In both cases, AERMOD is shown to be overly sensitive to building width, largely overpredicting for a cubic building when the stack height is equal to the building

---

[1] Translation: Operational Meteorological Air Quality Model

height and largely underpredicting for a wide building when the stack height is 1.5 times the building height.

### de Melo, et al., 2012

The PRIME model in both AERMOD and CALPUFF were evaluated against wind tunnel results for a building complex at a swine farm. The structure is L-shaped with a long, wide stem and a much shorter, narrower base. Four wind directions, each perpendicular to a different building face, were simulated. AERMOD and CALPUFF performed similarly, though AERMOD had a general tendency to predict higher concentrations than CALPUFF regardless whether both models were under or overpredicting. In the near-wake, AERMOD underpredicted centerline concentrations for three of the simulations and overpredicted for the fourth. Neither AERMOD nor CALPUFF were able to simulate a lateral shift of the plume and the location of the maximum concentration. Further downwind from the building, AERMOD performed well for three of the simulations, but again overpredicted by as much as a factor of 2 for one building face. The performance of both AERMOD and CALPUFF improved with increasing distance downwind of the building.

### Perry, et al., 2016

Past research has shown that for buildings rotated relative to the wind direction, the maximum ground-level concentration shifts laterally along the lee side of the building rather than occurring downwind (Huber, 1989; Snyder, 2005). This lateral shift can be as much as four times the building height for an elongated building rotated 45 degrees relative to the wind. AERMOD/PRIME does not account this shift. A wind tunnel study was recently conducted by the EPA to better characterize pollutant dispersion near elongated buildings and evaluate the performance of AERMOD/PRIME. Simulations were performed for elongated buildings with varied dimensions, a single stack at varied heights and locations, with the building perpendicular to the wind and rotated to different angles. Ground-level concentrations and the location of the maxima for elongated buildings are largely influenced by wind direction with a greater sensitivity when the stack is located near a corner of the building. Lateral dispersion increases with increased building width. In general, Perry et al. found that AERMOD tends to overpredict plume spread, underestimate rate of decrease of the effective height of the plume with distance, and underpredict maximum ground-level concentrations.

### Petersen, et al., 2017

Based on computational fluid dynamics (CFD) simulations and wind tunnel studies, Petersen et al. offer potential solutions to theoretical deficiencies in the PRIME model as implemented in AERMOD and BPIPPRM. A few of these issues are summarized here.

Turbulence intensity used to calculate the horizontal and vertical dispersion coefficients increases unrealistically by a constant factor from the ground to the height of the wake. While the wake height calculation, is found to be valid, the calculation of turbulence intensity is over-simplified and needs to be researched further. A related issue is the depth of the high turbulence region in PRIME which is sometimes exaggerated and extends too far above the building height. This can exaggerate building downwash resulting in higher concentrations in the near-wake for shorter stacks.

For buildings that are angled to the wind, the effective building dimensions generated in BPIPPRM represent artificially large buildings. This also contributes to an exaggerated wake height at the lee edge of the building. Petersen et al. suggests updating BPIPPRM similar to the method used in the Danish

OML model in which the building length is equal to the length of the portion of the building traversed by the wind, and the width is the length of line across the building in the direction perpendicular to wind. A second approach offered preserves the building volume. Wind tunnel studies performed by Petersen suggest AERMOD could be improved by modifying AERMOD to maintain horizontal streamlines for porous and lattice structures.

Also discussed are the issues with streamline slope discontinuity, the corner vortex, and upwind terrain wakes.

## Considerations for Updates in Model System

EPA is aware of two initiatives that are underway to improve the treatment of downwash in AERMOD.

1) Wind tunnel experiments and the use of embedded large eddy simulations (LES) by the EPA's Office of Research and Development (ORD) are ongoing to determine how to better parameterize buildings that are elongated and angled relative to the wind flow. EPA's Air Quality Modeling Group anticipates this research will result in recommendations for improving BPIPPRM and AERMOD/PRIME. The ORD studies are concentrated on known issues with single rectangular buildings, specifically investigating changes in plume parameters at discrete downwind distances from the building and source, longitudinal and lateral plume profiles, the lateral plume shift on the lee side of rotated buildings, and building characterization in BPIPPRM (Heist et al., 2016). Two related manuscripts are currently under journal review that propose improvements to BPIPPRM and the PRIME algorithms.

2) A PRIME2 Advisory Committee has been formed by the Atmospheric Modeling and Meteorology subcommittee of the Air and Waste Management Association. The PRIME2 committee was created for the purpose of providing a technical review forum to suggest improvements to the PRIME model and establish a process to review, approve, and implement new science into PRIME. The PRIME2 committee is investigating many of the issues discussed by Petersen et al. (2017) and have recommended updates to PRIME and submitted them for EPA to review and consider.

EPA will continue with downwash research and investigate potential improvements to the treatment of building downwash in AERMOD, engaging with the scientific and stakeholder community through ORD. Improvements to AERMOD will be based on scientific, peer reviewed research to ensure it has been vetted through the scientific community. EPA's Air Quality Modeling Group will consider the inclusion of beta options in AERMOD that reflect EPA/ORD or other sponsor peer-reviewed research on near-term improvements to BPIPPRM and the PRIME algorithm. In the longer-term, EPA will consider peer-reviewed research that provides for science updates to or replacement of the current PRIME algorithms.

## References

de Melo, A.M.V, J.M. Santos, I. Mavroidis and N.C. Reis Jr. (2012). Modelling of odour dispersion around a pig farm building complex using AERMOD and CALPUFF. Comparison with wind tunnel results. Building and Environment, 56, 8-20.

EPRI. (1997). Addendum to ISC3 User's Guide: The PRIME Plume Rise and Building Downwash Model. Submitted by the Electric Power Research Institute (EPRI). November 1997.

Heist, D., Perry, S., Monbureau, E., Brouwer, L., and L. Brixey. (2016). An overview of recent building downwash research at EPA/ORD. U.S. Environmental Protection Agency. 2016 Regional, State, and Local Modelers' Workshop, RTP, NC. November 15-17, 2016.

Huber, A.H. (1989). The influence of building width and orientation on plume dispersion in the wake of a building. Atmos. Environ. 23, 2109-2116.

Olesen, H.R., Berkowicz, R., Ketzel, M., Lofstrom, P. (2009). Validation of OML, AERMOD/PRIME and MISKAM using the Thompson wind tunnel data set for simple stack-building configurations. Boundary-Layer Meteorol. 131, 73-83.

Perry, S.G., Heist, D.K., Brouwer, L.H., Monbureau, E.M., and L.A. Brixley (2016). Characterization of pollutant dispersion near elongated buildings based on wind tunnel simulations, *Atmospheric Environment*, Vol. 42, 286-295.

Ron L. Petersen, Sergio A. Guerra & Anthony S. Bova. (2017). Critical Review of the Building Downwash Algorithms in AERMOD. J. Air Waste Management Association Vol. 67, Issue 8.

Schulman, L. L., D. G. Strimaitis, and J. S. Scire. (2000). Development and evaluation of the PRIME plume rise and building downwash model. J. Air Waste Management Association, 50**,** 378-390.

Snyder, W.H. (2005). Streamline patterns around buildings deduced from windtunnel measurements. In: International Workshop on Physical Modelling of Flow and Dispersion Phenomena (PHYSMOD). London, Ontario, Canada.

Thompson, RS. (1993). Building amplification factors for sources near buildings—a wind-tunnel study. Atmos Environ A Gen 27:2313–2325.

# $NO_2$ Modeling Techniques

## Overview of Issue

The $NO_2$ modeling techniques currently available in AERMOD estimate the NO-to-$NO_2$ conversion via ozone in order to estimate total $NO_2$ impacts (which include both the converted NO and the emitted $NO_2$). The techniques available to estimate this conversion have three “tiers”, with varying degrees of complexity, but even the most advanced Tier 3 techniques (*i.e.*, the Ozone Limiting Method, OLM, and the Plume Volume Molar Ratio Method, PVMRM), are considered screening rather than refined modeling techniques. As screening techniques, their use in regulatory applications should occur in agreement with the appropriate reviewing authority (paragraph 3.0(b) of Appendix W).

The EPA has not been able to identify either OLM nor PVMRM to be part of the preferred version of AERMOD modeling system for use as a refined model for all applications. This is due to two primary factors:

1. OLM and PVMRM both have known limitations as to which source types and configurations for which they work best. PVMRM is known to work best with relatively isolated sources, but it can potentially overestimate the NO-to-$NO_2$ conversion when plumes have significant overlap, as it can overestimate the amount of entrained ozone. OLM is somewhat less sophisticated than PVMRM as it does not estimate entrained ozone, but bases the NO-to-$NO_2$ conversion on the total amount of ozone present in the atmosphere. Thus, there appears to be a fundamental need for a refinement to PVMRM or OLM or an alternative Tier 3 model that addresses these limitations.
2. The databases available to evaluate $NO_x$ emissions and NO-to-$NO_2$ conversion have several limitations, mainly uncertainty in the emissions and characterization of on-site ozone data. As a result, they are not of sufficient quality to make a determination of preference based on model performance. Thus, there is a need for additional field study databases with sufficient information to inform the preferred model selection process.

## Current Implementation in AERMOD

AERMOD currently has multiple techniques to model $NO_2$ concentrations, all of which are considered screening techniques. Per Section 4.2.3.4 of the Guideline, the EPA recommends that $NO_2$ modeling should be done as a three-tiered screening approach, where each tier increases in complexity and decreases in conservativeness. The first tier is total conversion, so all emitted $NO_X$ is immediately converted to $NO_2$. The second tier is the Ambient Ratio Method, ARM or ARM2. The ARM method and an updated ARM2 method are included in the most recent release of AERMOD, v16216r. [1] The ARM method uses a default ambient ratio to estimate NO-to-$NO_2$ conversion for all applications (0.75 as the default ratio for annual $NO_2$ and 0.80 as the default ratio for hourly $NO_2$). ARM2 adjusts the modeled $NO_X$ concentrations based on an empirical relationship between ambient $NO_X$ and ambient $NO_2$ concentrations. The third tier consists of two options: 1) the Ozone Limiting Method described by Cole and Summerhays (1979), and 2) the Plume Volume Molar Ratio Method developed by Hanrahan (1999). OLM uses the assumption that either Ozone ($O_3$) or available $NO_X$ is the limiting factor in the reaction of NO with $O_3$ to form $NO_2$. PVMRM estimates the amount of ozone entrained in the dispersion plume of a

---

[1] Though the original ARM method is included in the current version of AERMOD as an NOx conversion option, the updated *Guideline* specifies ARM2 as the preferred Tier 2 method.

source to determine the amount of ozone that is available for oxidation of NO to form $NO_2$, then applies a limiting factor approach. Based on the recent revisions to the *Guideline*, the latest release of AERMOD, v16216r, includes a formulation update to PVMRM to provide more accurate calculations of dispersion plume volumes, especially for stable atmospheric conditions.

## Summary of Current Literature or Research

### Carruthers et al., 2017

This work documents the development of a technique to more accurately model chemical reactions to form $NO_2$, called the Atmospheric Dispersion Model Method, ADMSM. The ADMSM uses similar calculations for plume entrainment as PVMRM, but adds a “reaction rate” based on solar radiation and travel time from source to receptor. The reaction rate is based on the generic reaction set (GRS) chemistry scheme for multiple step conversions between NO, $NO_2$, and $O_3$. The authors provide comparisons of the two current AERMOD tier three methods, OLM and PVMRM (updated) to the ADMSM for four data sets. OLM showed the worst performance, because of its inherent method of maximum conversion. PVMRM showed better performance, because of the entrainment aspect of the calculation. ADMSM showed the best performance by including the entrainment methodology with the addition of travel time to calculate a reaction rate sing GRS.

## Considerations for Updates in Model System

### Updates to $NO_2$ Tier 3 methods in the modeling system

The American Petroleum Institute (API) is currently working with the Atmospheric Dispersion Modeling System (ADMS) model developers (CERC) in the UK to implement the ADMS $NO_2$ chemistry scheme into AERMOD. This scheme is documented in the Carruthers (2017) article detailed above. An initial version of this $NO_2$ scheme integrated into AERMOD was shared with the EPA’s Air Quality Modeling Group in June of 2015. API is currently working with CERC to provide the EPA with an updated version of this approach. Once received, the EPA will evaluate this new method for consideration as an alternative model (i.e., beta option) for use as a Tier 3 method in AERMOD for $NO_2$ modeling. This could be available for public release in late 2018.

### Database development and assessments of Tier 3 methods

Over the past several years, there have been several externally (non-EPA) funded field studies focused on $NO_X$ emissions, some of which had the specific goal of providing a field database for model evaluation. The EPA is leading two workgroups that are evaluating these field studies for use as model evaluation databases. This evaluation will eventually result in new databases for public evaluations as well as peer-reviewed journal articles assessing model performance. It is hoped that these databases can be information that can help determine if the ADMS or other iterations of OLM or PVMRM can be considered as a refined model for specific cases, determine if a single model can be identified as a preferred model, or be used in the further development of an alternative Tier 3 method.

## References

Carruthers, D.J., Stocker, J.R., Ellis, A., Seaton, M.D. and Smith, S.E. (2017). Evaluation of an explicit $NO_X$ chemistry method in AERMOD. Journal of the Air & Waste Management Association, 67(6), pp.702-712.

Cole, H.S. and Summerhays, J.E. (1979). A review of techniques available for estimating short-term $NO_2$ concentrations. Journal of the Air Pollution Control Association, 29(8), pp.812-817.

Chu, S., Meyer, E. (1991). Use of ambient ratios to estimate impact of $NO_X$ sources on annual $NO_2$ concentration. In: Annual Meeting of the Air and Waste Management Association, Vancouver, British Columbia.

Hanrahan, P.L. (1999). The plume volume molar ratio method for determining $NO_2/NO_X$ ratios in modeling—Part I: Methodology. Journal of the Air & Waste Management Association, 49(11), pp.1324-1331.

Podrez, M. (2015). An update to the ambient ratio method for 1-h $NO_2$ air quality standards dispersion modeling. Atmospheric Environment, 103, pp.163-170.

# Mobile Source Dispersion Modeling

## Overview of Issue

There are several potential improvements to consider for future versions of AERMOD, including increasing the options for modeling mobile source line sources (i.e., highway and intersection projects), as well as accounting for different types of roadway design. The recent revisions to the *Guideline* included the replacement of CALINE3 with AERMOD as the preferred dispersion model for refined applications for roadway projects[1]. These regulatory applications include mobile source modeling for transportation conformity hot-spot analyses for particulate matter ($PM_{2.5}$ and $PM_{10}$) and carbon monoxide (CO).

Currently, AERMOD is used to model air quality from roadways using an elongated area source or a set of volume sources, though it does not contain a “true” non-buoyant line source. The area source approach may be relatively easy to implement, but the area source algorithms do not consider plume meander under low wind conditions, which can be particularly important for surface releases. The volume source approach included in the current version of AERMOD does consider plume meander under low wind conditions, but can be more complex to implement due to the number of sources required and the limitations that can exist for receptor placement for volume sources. EPA’s PM Quantitative Hot-spot guidance discusses the use of area and volume sources to model air quality from roadways. [2]

R-LINE is a Research LINE source model, developed by EPA’s Office of Research and Development (ORD). R-LINE uses state-of-the-art Gaussian dispersion algorithms, similar to AERMOD, and contains a “true” line source algorithm based on Romberg integration of point sources (Snyder et al., 2013a), it is tailored to roadway applications, and it considers plume meander under low wind conditions. R-LINE and its algorithms may offer an additional pathway for future modeling of mobile sources.

In addition, AERMOD does not contain algorithms to account for dispersion around solid noise barriers near roadways and roadways within a depression. However, R-LINE has beta implementation of solid barrier and depressed roadway algorithms for modeling complex roadway configurations. These algorithms are still under development by ORD, but there is an opportunity to include them once they have been appropriately evaluated and peer-reviewed (*e.g.*, journal publication).

## Current Implementation in AERMOD

AERMOD is currently capable of modeling a line source as either an area or volume source. The current implementation of the “LINE” source type represents a source as an elongated area source, which does not include considerations for low wind conditions (i.e., meandering). Volume sources, which can also be used to model line sources, however, have a treatment of meander which accounts for the contribution of emissions in the downwind dispersion plume. The volume source method is

---

[1] While AERMOD has been identified as the preferred model for refined mobile source modeling, the EPA has retained the CAL3QHC model as the preferred screening approach for CO screening demonstrations of highway projects. However, AERMOD can still be used for such screening demonstrations when paired with screening meteorology generated from MAKEMET. See the Technical Support Document provided as part of the Appendix W FRM package (U. S. EPA, 2016).

[2] Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM2.5 and PM10 Nonattainment and Maintenance Areas, EPA Office of Transportation and Air Quality, EPA-420-B-15-084, November 2015.

computationally accurate and contains low wind meandering treatment, but is computationally intensive due to the number of sources needed to meet the AERMOD volume source criteria. The current area and volume approaches do not include noise barriers next to roadways and roadways depressed below the surrounding terrain.

## Summary of Current Literature or Research

### R-LINE Dispersion Model

#### *Snyder et al., 2013a*

This work outlines the R-LINE model formulations as well as the integration scheme and model assumptions. The Romburg integration scheme is explained as approximating a line using an exact point source dispersion solution and the systematic addition of point sources until convergence at the receptor is reached. Special attention is paid to cases where the receptor is located very near the line source. In this case, a minimum number of iterations is required to ensure that the spacing between the points used to approximate the line source is smaller than the distance from receptor to the line.

A model performance evaluation is conducted where the R-LINE model is compared to the concentrations from the Idaho Falls line source tracer experiment (Finn et al., 2010), the CALTRANS Highway 99 real-world tracer study (Benson, 1992), and the 2006 near road study in Raleigh, North Carolina (Baldauf et al., 2008). The R-LINE model showed good performance in a variety of atmospheric conditions, including stable, neutral and convective conditions; in a variety of wind conditions, including low winds, high winds, and winds parallel to the road; and in a variety of configurations including upwind, downwind, and close to the source.

#### *Venkatram et al., 2013*

This work outlines the new formulation of the horizontal and vertical surface dispersion curves used in R-LINE. These new formulations are based on data from the 1958 Prairie Grass Project, 2008 Idaho Falls line source tracer experiment (Finn et al., 2010), and EPA's neutral boundary layer meteorological wind tunnel. This article describes performance of the current AERMOD dispersion curves versus the new R-LINE dispersion curves for the Idaho Falls line source experiment.

#### *Heist et al., 2013*

This work evaluated the performance of the R-LINE, AERMOD-AREA, AERMOD-VOLUME, CALINE, and ADMS models in two applications. The first application of the models was in the Idaho Falls tracer experiment (Finn et al., 2010), which used a grid of receptors placed predominately downwind of a simulated line source that emitted a tracer gas. The second application was in the CALTRANS Highway 99 study (Benson, 1992), in which a tracer gas was systematically released from vehicles traveling down a highway. Measurements were taken along the median of the divided highway and along a transect from 50 to 200 meters. The conclusion of this work is that CALINE (version 3 and 4) produced more scatter than the other models in the model to measurement comparisons. In addition, the R-LINE, AERMOD-AREA, AERMOD-VOLUME and ADMS, all performed well with similar results. Overall, R-LINE showed slightly better model performance than AERMOD-AREA and AERMOD-VOLUME.

### Barrier Algorithms

There have been multiple barrier algorithms proposed for inclusion to dispersion models, such as those presented by Schulte et al. (2014) and Venkatram et al. (2016). EPA's ORD is still working with R-LINE to develop and evaluate algorithms to simulate the effects of solid barriers near roadways. This work is ongoing and will utilize measurements take in EPA's wind tunnel (Heist et al., 2009), during the Idaho Falls experiment (Finn et al., 2010), the Raleigh near road study in 2006 (Baldauf et al., 2008), and the Phoenix, Arizona field study (Baldauf et al., 2016). However, these studies are limited in their range of meteorological conditions, duration, and variety of noise barrier characteristics (*e.g.* distance from roadway, height, and multiple barriers) studied.

### Depressed Roadway Algorithm

There has been less work conducted on the development of depressed roadway algorithms in comparison to barrier algorithms. EPA's ORD is working to develop and evaluate a depressed roadway algorithm as part of R-LINE, utilizing wind tunnel studies (Heist et al., 2009) and the 2008-2009 field study in Las Vegas (Kimbrough et al., 2013; Baldauf et al., 2013).

## Considerations for Updates in Model System

The EPA is currently working with the Federal Highway Administration (FHWA) on a joint initiative through a formal Interagency Agreement (IA) to advance several aspects of air quality dispersion modeling for mobile sources. In particular, the IA is the primary funding mechanism for a project to incorporate the R-LINE algorithms into AERMOD. The IA also provides funding to EPA's ORD to supplement existing efforts to conduct wind tunnel studies to further refine and develop solid barrier algorithms.

The primary focus of the IA is the creation of a new "RLINE" source type into the AERMOD modeling system. This work will implement the current R-LINE algorithms to simulate dispersion from line sources, such as roadways. The RLINE source type will contain the newly formulated surface dispersion parameterizations and will have features tailored to roadways. Incorporation of R-LINE will include model functionality extensions to utilize AERMOD's emissions processing for temporally variable emissions. This RLINE source type will be added as a beta option. The EPA plans to have an internal draft of the R-LINE integration by mid-2018, with a potential beta release in the public version of AERMOD in late 2018.

R-LINE and its algorithms are still being researched and developed, especially the roadway configurations for barriers and depressed roadways. EPA's ORD, partly in coordination with the FHWA IA, continues to take wind tunnel measurements to refine and improve these algorithms, but a database of relevant field studies highlighting these source configurations is needed. Once these algorithms have been thoroughly tested they could be incorporated into the RLINE source type. Their initial incorporation will be in an alpha form to allow testing and evaluation before they would be publicly released as a beta option(s) in AERMOD. The alpha (or beta) options would be available with the new RLINE source in AERMOD, so will potentially be available for public release in late 2018.

Any future release of AERMOD alpha and/or beta options would be available for testing and comment by the user community, and potential future incorporation into AERMOD for regulatory purposes.

## References

Baldauf, R., Thoma, E., Hays, M., Shores, R., Kinsey, J., Gullett, B., Kimbrough, S., Isakov, V., Long, T., Snow, R. and Khlystov, A. (2008). Traffic and meteorological impacts on near-road air quality:

Summary of methods and trends from the Raleigh near-road study. Journal of the Air & Waste Management Association, 58(7), pp.865-878.

Baldauf, R.W., Isakov, V., Deshmukh, P., Venkatram, A., Yang, B. and Zhang, K.M. (2016). Influence of solid noise barriers on near-road and on-road air quality. Atmospheric Environment, 129, pp.265-276.

Baldauf, R.W., Heist, D., Isakov, V., Perry, S., Hagler, G.S., Kimbrough, S., Shores, R., Black, K. and Brixey, L. (2013). Air quality variability near a highway in a complex urban environment. Atmospheric environment, 64, pp.169-178.

Benson, P.E. (1992). A review of the development and application of the CALINE3 and 4 models. Atmospheric Environment. Part B. Urban Atmosphere, 26(3), pp.379-390.

Finn, D., Clawson, K.L., Carter, R.G., Rich, J.D., Eckman, R.M., Perry, S.G., Isakov, V. and Heist, D.K. (2010). Tracer studies to characterize the effects of roadside noise barriers on near-road pollutant dispersion under varying atmospheric stability conditions. Atmospheric Environment, 44(2), pp.204-214.

Heist, D.K., Perry, S.G. and Brixey, L.A. (2009). A wind tunnel study of the effect of roadway configurations on the dispersion of traffic-related pollution. Atmospheric Environment, 43(32), pp.5101-5111.

Heist, D., Isakov, V., Perry, S., Snyder, M., Venkatram, A., Hood, C., Stocker, J., Carruthers, D., Arunachalam, S. and Owen, R.C. (2013). Estimating near-road pollutant dispersion: A model inter-comparison. Transportation Research Part D: Transport and Environment, 25, pp.93-105.

Kimbrough, S., Baldauf, R.W., Hagler, G.S., Shores, R.C., Mitchell, W., Whitaker, D.A., Croghan, C.W. and Vallero, D.A. (2013). Long-term continuous measurement of near-road air pollution in Las Vegas: seasonal variability in traffic emissions impact on local air quality. Air Quality, Atmosphere & Health, 6(1), pp.295-305.

Schulte, N., Snyder, M., Isakov, V., Heist, D. and Venkatram, A. (2014). Effects of solid barriers on dispersion of roadway emissions. Atmospheric environment, 97, pp.286-295.

Snyder, M.G., Venkatram, A., Heist, D.K., Perry, S.G., Petersen, W.B. and Isakov, V. (2013a). RLINE: A line source dispersion model for near-surface releases. *Atmospheric environment*, *77*, pp.748-756.

Snyder, M.G. and Heist, D.K. (2013b). User's Guide for R-LINE Model Version 1.2: A Research LINE source model for near-surface releases. Atmospheric Modeling and Analysis Division.

U. S. EPA (2016). Technical Support Document (TSD) for Replacement of CALINE3 with AERMOD for Transportation Related Air Quality Analyses, EPA- 454/ B-16-006

U.S. EPA (2015). Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM2.5 and PM10 Nonattainment and Maintenance Areas, EPA-420-B-15-084

Venkatram, A., Snyder, M.G., Heist, D.K., Perry, S.G., Petersen, W.B. and Isakov, V. (2013). Re-formulation of plume spread for near-surface dispersion. Atmospheric environment, 77, pp.846-855.

Venkatram, A., Isakov, V., Deshmukh, P. and Baldauf, R., 2016. Modeling the impact of solid noise barriers on near road air quality. Atmospheric Environment, 141, pp.462-469.

# Overwater Dispersion Modeling

## Overview of Issue

For three decades, the Offshore and Coastal Dispersion Model (OCD) has been the EPA's preferred model (i.e. listed in Appendix A of the *Guideline*) for estimating near field air pollutant impacts from overwater emission sources, for both deep water and shoreline applications. OCD has remained the preferred model in these environments due to its treatment of downwash effects from raised, open offshore drilling platforms and the capability to model coastal fumigation at and beyond the shoreline.

The OCD model was developed in the early 1980's by the former Minerals Management Service (MMS), now the Bureau of Ocean Energy Management (BOEM). The EPA approved OCD version 3 (OCD3) as a preferred *Guideline* model in January 1988 (53 FR 392). The downwash algorithms in Version 3 were developed and tested for land-based structures rather than raised platforms and were updated in OCD version 4 (OCD4) in 1989 based on wind tunnel studies of offshore platforms by Petersen (1986). Version 4 also included science updates to the fumigation algorithms, the treatment of the dispersion coefficients sigma-y and sigma-z, plume reflection, the implementation of the critical streamline using the RTDM approach, and the addition of line and area source types (DiCristofaro et al., 1989). The subsequent release, version 5 in 1997 included a graphical user interface (GUI) to make the model more user friendly. Version 5 also included changes to the input data formats and pre- and post-processor programs, but no revisions were made to model formulation (Chang and Hahn, 1997). The last update to OCD occurred in January 2000, released as OCD5 version 00006 which included a few bug fixes as described in the OCD Model Change Bulletin #3.[1] Though OCD remains an EPA preferred model, it does not include the more recent scientific advancements reflected in the AERMOD modeling system. However, to consider replacing the OCD model with the AERMOD modeling system as the preferred model for overwater emission sources, EPA would need to incorporate science updates related to: 1) platform downwash, 2) shoreline/coastal fumigation, and 3) allow for better characterization of the marine boundary layer. The following briefly compares AERMOD and OCD with respect to these three needed updates to AERMOD:

- <u>Platform downwash</u>: The downwash algorithms in AERMOD were designed specifically to model downwash effects from solid, rectangular, ground-based structures. OCD better accounts for the flow under and through raised lattice structures common to deep water offshore drilling platforms.
- <u>Shoreline/coastal fumigation</u>: OCD can account for the location of the shoreline via user input and separately characterize the marine and over land boundary layers by accepting separate meteorological inputs for the two distinct boundary layer environments. By defining the two boundary layers, OCD can account for the Thermal Internal Boundary Layer (TIBL) which is responsible for fumigation. AERMOD is limited to a single set of boundary layer parameters which define a homogeneous boundary layer throughout the entire modeling domain without any spatial variability.

---

[1] https://www3.epa.gov/ttn/scram/mcbs/ocdz3.txt

- Marine boundary layer: AERMET, the meteorological processor for AERMOD, was designed to process land-based meteorology and does not account for the air-sea interactions needed to characterize the marine boundary layer.

## Current Implementation in AERMOD

### Platform Downwash

Building downwash is modeled in AERMOD using the Plume Rise Model Enhancements (PRIME) algorithms which are integrated into AERMOD for point sources. The development PRIME was sponsored by the Electric Power Research Institute (EPRI) with a focus on: 1) enhanced plume dispersion coefficients from the turbulent wake, and 2) reduced plume rise from descending streamlines in the lee of the building and the increased entrainment in the wake (EPRI, 1997).

PRIME is based on wind tunnel and field data collected for solid, ground-based structures and does not take into account air flow under raised buildings or through the lattice structures typical of offshore platforms. The PRIME model reduces plume rise based on streamline deflection near the building, vertical wind speed shear, enhanced dilution from the turbulent wake and reduction in velocity. Plume mass is partitioned between two wake regions: a near-wake cavity of recirculating mass adjacent to the building and a far-wake with enhanced dispersion. Dispersion of the recirculated cavity mass is based on building geometry and is assumed to be uniformly mixed. Mass is re-emitted from the cavity into the far-wake region at the boundary of the cavity and combined with the portion of the plume that was not drawn into the cavity. The rate of dispersion in the far-wake region is based on source location, release height, and building geometry. Dispersion in the near-wake is determined with a probability density function, while dispersion in the far-wake is based on an eddy diffusivity model. Beyond the wake, the total concentration at a given location is based on a weighting of the concentration computed by PRIME and the concentration computed by AERMOD ignoring downwash. The weighting parameter decreases exponentially with vertical, lateral, and downwind distance from the wake.

### Shoreline/Coastal Fumigation and Marine Boundary Layer

As stated previously, AERMOD cannot model shoreline/coastal fumigation. Furthermore, AERMET cannot adequately represent marine environments. The parameterization of the boundary layer by AERMET is based on surface and upper air meteorology collected at a single location to represent the entirety of the modeling domain. For most applications of AERMOD, the surface data are either hourly site-specific observations collected near the facility or National Weather Service (NWS) observations collected at a nearby airport. Upper air data are collected twice per day by the NWS. Observations of parameters such as wind speed, wind direction, temperature, and cloud cover are processed through the AERMET meteorological preprocessor to compute hourly values for boundary layer parameters such as surface friction velocity, Monin-Obukhov length, and mixing height. While the boundary layer varies with time, based on observations, AERMOD assumes it is uniform throughout the modeling domain for a given hour.

AERMET was designed for overland applications and assumes a diurnal cycle of heating and cooling of land surfaces in which heat flux at the surface is positive during the day and negative at night. This results in unstable conditions during the day and stable conditions at night. Diurnal patterns over large water bodies are far less dramatic than over land. This is due to the heat capacity of water compared to land surfaces. Water takes longer to heat up and retains heat much longer after the energy source is removed. Stability in the marine boundary layer is more of a response to air-sea temperature difference and wind speed than the diurnal heating and cooling of the surface. While there can be a stark contrast between the two atmospheric boundary layers at the shoreline interface, AERMOD knows of only one which is assumed to be land-based.

The AERCOARE program (EPA, 2012) has been developed as a preprocessor for overwater meteorological data as a counterpart to AERMET to better characterize the marine boundary layer. Though not yet part of the regulatory version of the AERMOD system, prior to the development of the AERCOARE program, the EPA Model Clearinghouse concurred with EPA Region 10's approval of the use the AERCOARE algorithms as an alternative program to preprocess meteorological data for applications in the Arctic ice-free environments of the Beaufort and Chukchi Seas (EPA, 2011). Until AERCOARE is adopted as a regulatory preprocessor for AERMOD, the EPA anticipates there will be additional requests to use AERCOARE which will, over time, establish a solid foundation for more timely approval per Appendix W, Section 3.2.2. However, the use of AERCOARE does not address the bigger issue of shoreline and coastal fumigation.

## Summary of Current Literature or Research

### Platform Downwash

The only research that EPA found related to downwash from raised platforms and porous and lattice structures is the original wind tunnel studies performed by Petersen (1986) which is implemented in OCD and subsequent wind tunnel studies performed by Petersen and Lout (2012).

#### *Petersen, 1986*

Petersen conducted wind tunnel experiments for offshore drilling platforms to assess the building wake algorithm in the OCD model. Experiments were performed for three typical oil platforms. Additional wind tunnel experiments were conducted to simulate two cases from a past tracer field experiment that had previously been carried out in the Gulf of Mexico (Dabberdt, et al., 1982). Petersen demonstrated that a raised platform can have a significant effect on dispersion, and that the formulation in the OCD model at the time was not sufficient. OCD underestimated the horizontal and vertical dispersion coefficients when there was a significant wake effect. Petersen proposed changes to the calculation of the dispersion coefficients which were incorporated into the OCD model with some modification based on the work of Hanna and DiCristofaro (1988). Petersen's work also demonstrated that the building height in OCD should be modified to be the height of the top of the platform relative to the sea surface rather than the height relative to the bottom of the platform. The platform downwash algorithm in the current version of the OCD model reflects the combined work of Petersen, Hanna, and DiCrisofaro as described in Volume I of the 1989 OCD4 User's Guide (MMS, 1989).

#### *Petersen and Lout, 2012*

While the majority of this work focuses on downwash issues related to the PRIME algorithms and the building preprocessor BPIPPRM, specific to rectangular solid structures, included is discussion on the streamline calculation for lattice and streamlined structures. Through wind tunnel experiments, Petersen and Lout demonstrated that lattice structures upwind or downwind of a stack enhances dispersion, but the streamlines remain horizontal and does not impact the ground close to the stack or structure as in the case of a solid building.

## Shoreline/Coastal Fumigation

Much of the literature found on shoreline and coastal fumigation dates back to the 1970's through the 1990's. While peer reviewed studies seem to be less prevalent today, the literature is not totally void. The following literature reflects much of the more recent work, recognizing that the structure of the TIBL is more complex than once thought.

### *EPA, 1987*

This work analyzed and evaluated two base shoreline fumigation models: the CRSTER Shoreline Fumigation Model (CSFM) and the Misra Shoreline Fumigation Model (MSFM) (Misra, 1980). Variations of the MSFM were also evaluated. The researchers found that the most significant factor affecting coastal dispersion is the shape of the TIBL. A steep TIBL results in higher concentrations closer to the stack. The study concluded that the MSFM was the better performer at predicting ground-level concentrations from stack releases at the shoreline, and convective velocity scaling is a better for characterizing dispersion in the TIBL than the standard Pasquill-Gifford curves. The MSFM was selected as the shoreline fumigation sub-model for the EPA's Shoreline Dispersion Model (SDM) (EPA, 1988) based on this analysis and evaluation.

### *Nazir et al., 2004*

This work discusses past probability density function (PDF) models and proposes an improved PDF model to predict coastal fumigation that is time efficient. The researchers used a convective limit assumed by Weil and Brower (1984) and the slab model to determine the height of the TIBL. Restricted to onshore flows and strong convection, the model is applicable in the range of $1.2 < U/w^* < 6$, where $U/w^*$ is a stability index in which U is the mean wind speed and $w^*$ is the convective velocity. The model also takes into account the skewness of the vertical convective turbulence which others do not. An error analysis demonstrates minimum error relative to observed values.

### *Yuan et al., 2006*

Observations from a tracer field experiment performed near the coast south of Los Angeles in Wilmington, CA were used to study the dispersion of near ground-level emissions in an urban coastal environment. Prior studies of coastal fumigation were primarily limited to plume behavior of elevated releases as they come into contact with the TIBL. This field study occurred during daytime hours during onshore flows. Tracer concentrations of SF6 were monitored along five arcs ranging from 100 to 5000 meters downwind of the emission source. The authors concluded that stable onshore flow can limit the height of the TIBL. The depth of the TIBL can be limited to a height of 150 m out to 5000 meters from the shoreline. In addition, the vertical dispersion of a ground-level source appears limited to the height of the capping stable overwater boundary layer that is advected with onshore flow. The authors also concluded that buildings near low-level releases affect the vertical spread of the plume and should be considered.

### *Park and Seok, 2007*

The focus of this work was to develop a new statistical approach for selecting an appropriate model applicable to coastal dispersion. The researchers developed a single statistical index using fuzzy inference in which eight different statistical measures (e.g., fractional bias, normalized mean square error, etc.) were taken as premise part variables. The method was evaluated using two different fumigation models and a total of eight modeling schemes based. In addition, the ISCST3 and ADMS3 models were also included. Using this new statistical approach, the Lyons and Cole (1973) fumigation model was found to be the better performer.

### *Hara et al., 2009*

Wind tunnel experiments and numerical simulations were performed for two temperature profiles to simulate the TIBL associated with a sea breeze. The two temperature profiles represented a weakly stratified and highly stratified case. The purpose of this work was to study the following: 1) the effect of atmospheric stability over the sea on the streamwise change in the turbulent structure, 2) transport processes in the TIBL, and 3) the growth of the TIBL. Wind tunnel experiments were performed in a thermally stratified wind tunnel. Numerical simulations were performed using a finite-difference method for a volume that was 11 m long, 1.6 m wide, and 1 m high. The governing equations included the Navier-Stokes, continuity, and energy equations. Changes in the mean temperature and wind speed in the lower layer suggest the TIBL developed due to heating the land surface while vertical profiles of temperature, heat flux, and turbulence changed as expected with increasing distance inland. Turbulence statistics in the TIBL varied accordingly with the temperature profile. The estimated TIBL heights from the wind tunnel and numerical simulations were in good agreement suggesting also that wind tunnel and numerical simulations reproduced the growth of the TIBL.

### *Calmet and Mestayer, 2015*

Calmet and Mestayer used large eddy simulation (LES) with high spatial resolution to research the identification of the TIBL and TIBL growth mechanisms. When the TIBL is impeded by topography, it can degenerate and difficult to identify by changes in the temperature. Their concluded that the best method for determining the TIBL depth is by using the minimum of the heat flux profiles. With regard to TIBL growth, using the ratio of friction velocity scale (u*) to the convective velocity scale (w*), they found that buoyancy is the dominant mechanism when u*/w* < 0.35 and shear is dominant when u*/w* > 0.35. The height of the TIBL is constant when u*/w* is between 0.35 – 0.5, and the height of the TIBL decreases when u*/w* > 0.5.

## Marine Boundary Layer

### *Wong, et al., 2016*

This work describes the AERCOARE meteorological processor which incorporates the Coupled Ocean-Atmosphere Response Experiment (COARE) algorithms for predicting air-sea energy fluxes. AERCOARE was developed as an alternative to the AERMET meteorological processor to more appropriately characterize the marine boundary layer when using AERMOD rather than OCD to model offshore emission sources. Wong et al. summarize the differences between AERMOD and OCD and the benefits and disadvantages of each model when modeling overwater sources. The paper presents the results of an AERMOD performance evaluation that utilized AERCOARE to process meteorological data collected during four past overwater field studies of offshore emissions including Cameron, Louisiana; Carpinteria, California; Pismo Beach, California; and Ventura, California. The same studies were previously used to develop the OCD model and evaluation the CALPUFF model which contains the COARE algorithms. The researchers found that predicted concentrations were generally within a factor of two of the observed frequency distributions for three of the four field studies and comparable to both OCD and CALPUFF for the same field studies. Wong et al. concluded that AERMOD, utilizing meteorological data processed with AERCOARE was a viable alternative to the OCD model for many overwater regulatory applications.

## Considerations for Updates in Model System

Multiple initiatives are ongoing to collaborate with other federal agencies to address these overwater issues including the establishment of a team under the Interagency Workgroup on Air Quality Modeling (IWAQM) that provides for specific coordination with the Department of Interior (DOI)'s Bureau of Ocean Energy Management (BOEM). The IWAQM Overwater Team is expected to provide a forum for improving and/or developing air quality models and techniques for assessments of ambient air quality impacts that support Outer Continental Shelf (OCS) and other overwater regulatory applications. This partnership between EPA and BOEM will have a specific focus on near-field and long-range transport modeling of overwater emissions sources used to ensure compliance with National Ambient Air Quality Standards (NAAQS), Prevention of Significant Deterioration (PSD) increments, and visibility impact assessments for Class I areas. The IWAQM Overwater Team would also support ongoing and future studies, including research in marine and coastal water environments, necessary to refine and/or develop the aforementioned air quality models and techniques.

<u>Platform downwash</u>: EPA's Air Quality Modeling Group will leverage off of current and future work performed by the Office of Research and Development (ORD) focused on the downwash issues in AERMOD. ORD is currently conducting wind tunnel experiments and large eddy simulations (LES) to investigate deficiencies with the PRIME algorithms and the parameterization of buildings, particularly elongated buildings rotated from perpendicular relative to the wind flow.

In addition, a PRIME2 Advisory Committee has been formed by the Atmospheric Modeling and Meteorology subcommittee of the Air and Waste Management Association (AWMA). The PRIME2 committee was created for the purpose of providing a technical review forum to suggest improvements to the PRIME model and establish a process to review, approve, and implement new science into PRIME. The PRIME2 committee is investigating the issue of platform downwash, among others downwash issues (Petersen and Lout, 2012), and have recommended updates to PRIME and submitted them for EPA to review and consideration.

We will consider the inclusion of beta options in AERMOD that reflect peer-reviewed EPA/ORD research as well as peer-reviewed research presented by the PRIME2 committee related to near-term improvements to BPIPPRM and the PRIME algorithm to address platform downwash or a replacement of the current PRIME algorithm.

<u>Shoreline/coastal fumigation</u>: EPA will review the current shoreline fumigation models including the older screening algorithms in AERSCREEN and SCREEN3, the SDM based on the work of Mirsa (1980), and the more recent work discussed in the previous section. In collaboration with other federal agencies and the broader scientific community, EPA will identify an appropriate shoreline fumigation formulation and determine a path for inclusion into AERMOD.

<u>AERCOARE:</u> EPA will consider incorporating the COARE algorithms into AERMET to process the information similar to what is done with prognostic data (provided via MMIF tool) and then conduct the necessary testing and evaluations of the AERMOD modeling system.

## References

Calmet, I. and Patrice Mestayer. (2015). Study of the thermal internal boundary layer during sea-breeze events in the complex coastal area of Marseille. Theoretical and Applied Climatology. 123, 801-826.

Chang, J.C. and K.J. Hahn, 1997. User's Guide for the Offshore and Coastal Dispersion (OCD) Model Version 5. MMS Contract No. 1435-96-PO-51307, November, 1997.

Dabberdt, W. F., R. Brodzinsky, B. C. Contrell, R. E. Ruff, and S. Sethuraman. (1982). Atmospheric Dispersions Over Water and in the Shoreline Transition Zone. Prepared by SRI International, Menlo Park, CA, for the American Petroleum Institute, Washington, DC, December 1982.

DiCristofaro, D.C. and S.R. Hanna. OCD The Offshore and Coastal Dispersion Model, Version 4, Volume I: User's Guide. MMS Contract No. 14-12-001-30396, November 1989.

EPA. (2012). User's Manual: AERCOARE Version 1.0. U.S. Environmental Protection Agency. EPA 910-R-12-008. October 2012.

EPA. (2011). Memorandum: Model Clearinghouse Review of AERMOD-COARE as an Alternative Model for Application in an Arctic Marine Ice Free Environment. From George Bridges, EPA Model Clearinghouse Director, to Herman Wong, EPA Regional Atmospheric Scientist, Office of Environmental Assessment, OEA-095, EPA Region 10, May 6, 2011.

EPA. (1988). User's Guide to SDM – A Shoreline Dispersion Model. U.S. Environmental Protection Agency. EPA-450/4-88-017. September 1988.

EPA. (1987). Analysis and Evaluation of Statistical Coastal Fumigation Models. U.S. Environmental Protection Agency. EPA-450/4-87-002. February 1987.

EPA. (1980). User's Guide for MPTER: A Multiple Point Gaussian Dispersion Algorithm with Optional Terrain Adjustment. U.S. Environmental Protection Agency. EPA-600/8-80-016. April 1980.

EPRI. (1997). Addendum to ISC3 User's Guide: The PRIME Plume Rise and Building Downwash Model. Submitted by the Electric Power Research Institute (EPRI). November 1997.

Hanna, S.R., L.L. Schulman, R.J. Paine, J. Pleim, and M. Baer. (1985). Development and Evaluation of the Offshore and Coastal Diffusion Model. J. Air Poll. Control Assoc., 16, 1039-1047.

Misra, P. K., and McMillan. (1980). On the Dispersion Parameters of Plumes from Tall Stacks in a Shoreline Environment. Boundary-Layer Meteorology, 19, 175-185.

MMS. (1989). OCD: The Offshore and Coastal Dispersion Model, Volume I: User's Guide. Report No. A085-1, Minerals Management Service (MMS), U.S. Department of the Interior, November.

Nazir, M., F. I. Khan, and T Husain. (2004). Revised estimates for continuous shoreline fumigation: a PDF approach. Journal of Hazardous Materials. A118, 53-65.

Park, O., M. Seok. (2007). Selection of an appropriate model to predict plume dispersion in coastal areas. Atmospheric Environment. 41, 6095-6101.

Petersen, R. L. (1986). Wind Tunnel Investigation of the Effect of Platform-Type Structures on Dispersion of Effluents from Short Stacks. JAPCA, 36, 1347-1352.

Petersen, R. L. and A. Beyer-Lout. (2012). AERMOD building downwash and theoretical limitations and possible solutions. 105 Annual Conference and Exhibition of the Air & Waste Management Association. Paper no. 2012-A-387-AWMA. San Antonio, Texas. June 2012

Schulman, L. L., D. G. Strimaitis, and J. S. Scire. (2000). Development and evaluation of the PRIME plume rise and building downwash model. J. Air Waste Management Association, 50**,** 378-390.

Turner, D.B. (1970). Workbook of Atmospheric Dispersion Estimates. Revised, Sixth printing, Jan. 1973. Office of Air Programs Publication No. AP-26.

Weil, J.C. and P.R. Brower. (1984). Estimating convective boundary layer parameters for diffusion applications, in: Maryland Power Plant Siting Program Rep. PPSP-MP-48, Department of Natural Resources, Annapolis, MD, 1984, 37 pp.

Wong, H., Elleman, R., Wolvovsky, E., Richmond, K. and J. Paumier. (2016). AERCOARE: An overwater meteorological preprocessor for AERMOD. J. Air Waste Management Association, 66:11, 1121-1140, DOI: 10.1080/10962247.2016.1202156.

Yuan, J., Venkatram, A., and Vlad Isakov. (2006). Dispersion from ground-level sources in a shoreline urban area. Atmospheric Environment, 40:1361-1372.