Building Downwash Alpha Options in AERMOD

To improve model performance for point emission sources that are subject to building downwash, EPA is updating the AERMOD dispersion model to include related alpha options for testing and evaluation. EPA anticipates the combination of these options, in full or in part, will be promulgated as formulation updates to the regulatory version of AERMOD, during the next revision to Appendix W of 40 CFR Part 51, the *Guideline on Air Quality Models (Guideline)*. This paper describes the current implementation of building downwash in AERMOD, limitations identified that potentially affect performance, current ongoing research initiatives, and the alpha options that are being added for testing and evaluation.

Current Implementation of Building Downwash in AERMOD

The treatment of downwash in AERMOD is based on the Plume Rise Model Enhancements (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).

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 given location (receptor) 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.

The PRIME model requires building dimensions, including along-wind building length (BUILDLEN), across-wind building width (BUILDWID), and building height for 36 wind flow vectors (every 10 degrees) relative to each stack. The PRIME model assumes the wind is always perpendicular to the building face. The building dimensions for the influencing tier for each stack and flow vector are determined by the Building Profile Input Program for PRIME (BPIPPRM) (EPA, 1993). Each stack is evaluated by BPIPPRM to determine if it is affected by building downwash based on Good Engineering Practice (GEP) stack height and nearby buildings within a 5L area of influence, where L is the lessor of the building height and projected building width (EPA, 1985). For multi-tiered buildings, each tier is treated like a separate stand-alone structure. BPIPPRM determines effective building dimensions for each flow vector based on a projected rectangular building as if the building were rotated to be perpendicular to the wind. The lengths and widths that are input to PRIME represent the along-flow and across-flow distances across the projected building. Two additional parameters computed by BPIPPRM are the along-flow and across-flow distances from the stack location to the center of the upwind face of the projected building for each of the 36 flow vectors.

Limitations of PRIME in AERMOD

Recent research (Foroutan et al., 2018; Heist et al., 2016; Monbureau et al., 2018; Perry et al., 2016; Petersen and Guerra, 2018; Petersen et al., 2017) has identified several limitations in the PRIME algorithm in AERMOD that could be contributing, at least in part, to the performance of AERMOD when building downwash is considered. These include the following:

- Exaggerated equivalent building dimensions;
- Boundaries of enhanced turbulence in the building wake;
- Assumed constant turbulence in the building wake;
- Upwind roughness and stability are not considered;
- Discontinuities in streamline calculations at the boundary of the near-wake and far-wake; and
- All structures are assumed rectangular and solid.

Downwash Research and EPA Collaboration

EPA's Air Quality Modeling Group (AQMQ) is collaborating on two separate research initiatives to improve AERMOD's performance with regard to point emission sources that are subject to building downwash. The first is an initiative led by the EPA's Office of Research and Development (ORD). ORD has performed wind tunnel experiments and embedded large eddy simulations (LES) to better understand how to parameterize buildings that are elongated and angled relative to the wind flow and the parameterization of the plume in the cavity and far wake regions. The ORD studies are concentrated on 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). To date, this research has led to recommended changes to the building preprocessor, BPIPPRM, as well as changes to the building downwash algorithm in the AERMOD program.

A second research initiative is being carried out by the PRIME2 Advisory Subcommittee (PRIME2) within the Atmospheric Modeling and Meteorology (APM) Committee of the Air and Waste Management Association (A&WMA). This effort involves the collaboration of technical experts, industry groups, and representatives from the regulatory agencies with the purpose of (1) providing a technical review forum to improve the PRIME building downwash algorithms in AERMOD; and (2) establishing a mechanism to review, approve, and implement new science into the model. PRIME2's research has included the reanalysis of existing wind tunnel data, as well as the completion of new wind tunnel experiments to investigate the decay of the building wake above the top of the building, appropriate height at which approach turbulence and wind speed are calculated, the reduction of wake effects for streamlined structures, and the effect of approach roughness on the wake. Their analyses have led to recommendations for new turbulence enhancement and velocity deficit equations that address these aspects.

Alpha Options

The recommended changes proposed by ORD and PRIME2 have been implemented in the AERMOD dispersion model as alpha options. Alpha options are non-default, non-regulatory options made available to the user community to facilitate testing and evaluation. The downwash alpha options have been implemented in a manner that individual components can be investigated separately and in combination with others to gain understanding of their singular and combined effects on model performance. Because there is some overlap in the recommendations from the two research initiatives, with a somewhat different approach and implementation, the options are segregated in AERMOD based whether the change was recommended by ORD or PRIME2. The different options will be employed by specifying option specific keywords in the AERMOD control file. EPA anticipates that the combination of all, or at least some subset, of the various options will be combined into a single option and promoted to beta status until promulgated as part of the formulation of the regulatory version of AERMOD.

ORD Alpha Options

ORD recommends changes to both the BPIPPRM building processor and the PRIME algorithm in AERMOD. ORD also recommends three updates to the PRIME calculations: (1) resolve the mismatch in plume width at the transition between the cavity and the far wake; (2) use an effective wind speed for the primary plume (instead of stack height wind speed); and (3) adjust the maximum ambient turbulence levels (Monbureau et al., 2018). These are each discussed in more detail in the subsequent sections.

Effective Building Dimensions

Based on a wind tunnel study of elongated buildings (Perry et al., 2016), ORD recommends a modification to BPIPPRM's projected effective length when winds are not directly incident on the face of the building. The study determined that the current version of BPIPPRM can lead to buildings with exaggerated footprints, resulting in significant impacts on streamlines and wakes surrounding the building. ORD has updated BPIPPRM which will be provided as a separate alpha version of BPIPPRM that defines the equivalent building dimensions based on the actual distance a parcel travels across the building that is angled to the wind, rather than the area that encompasses each of the vertices of the angled building if the area was rotated to be normal to the wind. This reduces the along-flow effective building length which consequently, reduces the size of the near-wake recirculation region. Figure 1, from Monbureau et al. (2018), illustrates the original building (light gray) at 15°, 30°, 45°, and 60° relative to the wind blowing from the west to the east and the projected, rotated building (dotted lines) prior to updating BPIPPRM. The dark gray illustrates the projected building based on ORD's proposed updates to BPIPPRM.

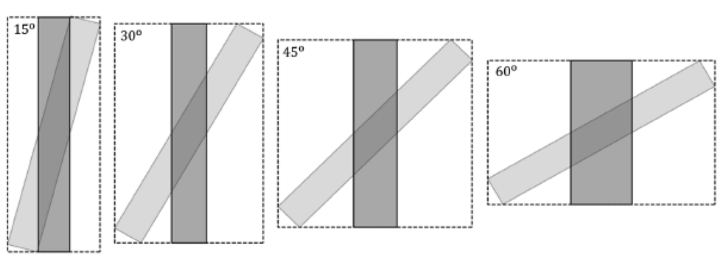

Figure 1. Projected Building using the BPIPPRM Algorithm (Monbureau et al., 2018).

Plume Spread Matching at Boundary Between Near-wake and Far-wake

The current implementation of PRIME creates a cavity plume and a re-emitted plume to simulate two distinct regions with a weighted distribution of mass between the two plumes. The cavity and re-emitted plumes initially have the same vertical dispersion on the leeward side of the building. The re-emitted plume grows with downwind distance while the vertical dispersion of the cavity plume remains unchanged throughout the cavity. This creates a discontinuity of the two plumes at the near-wake boundary results in a reduction in ground level concentrations. ORD has proposed eliminating this discontinuity such that the vertical dispersion of both plumes is equal at the cavity boundary. This change would result in an increase in the re-emitted plume concentration. Figure 2 illustrates the mismatch at the cavity boundary (LR) in the vertical dispersion (σz) of the re-emitted plume (solid line) which grows from the lee wall through the cavity and the cavity plume (dotted line) which is constant through the cavity.

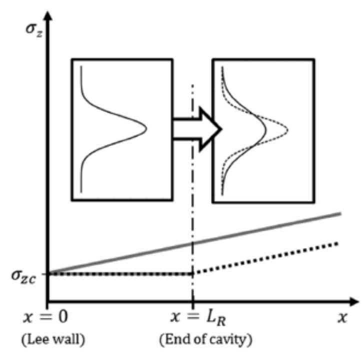

Figure 2. Discontinuity in vertical dispersion (σ_z) between the re-emitted plume (solid line) and the cavity plume (dotted line) at the cavity boundary (L_R). Inset: the vertical concentration profile within the cavity (left panel); the profile after plume is emitted from the cavity (solid line, original; dotted line, revised) (Monbureau et al., 2018).

Effective Wind Speed

The PRIME model currently uses the wind speed at stack height for the primary plume which likely under-estimates ground-level concentrations in the lee of the building. This is inconsistent with other source types in AERMOD where an effective wind speed (U_{eff}) is used. U_{eff} is defined as the averaged profiled wind speed between the receptor height and the plume centerline allowing the wind speed of the plume to change with a changing environment, such as the variability in surface roughness and stability. ORD has proposed the use of U_{eff} in PRIME which would result in a decrease in the wind speed toward the ground, i.e. the wind speed within the near-wake, thus increasing cavity concentrations (Monbureau et al., 2018).

Maximum Turbulence

Vertical and lateral dispersion coefficients are based on the formulations of Weil (1996). When PRIME was implemented in AERMOD, the maximum value of the ambient turbulence intensity in the wake was reduced from Weil's published value of 0.07 to 0.06. ORD has proposed increasing this maximum turbulence value to Weil's original value of 0.07. Increased turbulence brings the plume down toward the ground more quickly and increases the dispersion. This will result in reduced concentrations for the primary source and a shorter downwind distance to the maximum ground-level concentrations (Monbureau et al., 2018).

PRIME2 Options

PRIME 2 has proposed three updates to the PRIME model related to the effective wind speed of the primary plume, similar to ORD's proposal, and new formulations for turbulence enhancement and velocity deficit which incorporate building shape (streamline versus rectangular) and approach turbulence intensity (surface roughness), which will subsequently affect the calculations of plume rise and the dispersion coefficients in PRIME (Petersen and Guerra, 2018).

Effective Wind Speed

Similar to ORD, PRIME2 also proposed to redefine how the wind speed is determined for the primary plume, which is currently defined at the stack height. PRIME2 has proposed giving the user the control to define the height at which this wind speed should be calculated and provides recommended effective parameter values at a height of 30m when calculating wake turbulence (Petersen and Guerra, 2018).

Turbulence Enhancement and Velocity Deficit

In their analyses of wind tunnel data, PRIME2 has demonstrated that building wake effects decay rapidly back to ambient levels above the top of the building versus the current implementation in AERMOD in which wake effects can extend up to three building heights. In addition, the PRIME algorithm currently sets the lateral turbulence in the cavity equal to vertical turbulence, whereas, the wind tunnel shows that lateral turbulence is less than the vertical turbulence. Finally, the current PRIME algorithm does not account for the effects of approach roughness on the wake. PRIME2 has demonstrated that wake effects decrease as the approach roughness increases (Petersen et al., 2017).

PRIME2 has developed and proposed new formulations for turbulence enhancement and velocity deficit that address several of the limitations of PRIME previously mentioned including: rate of decay for building wake effects above the building, lateral turbulence enhancement in the wake, approach turbulence and wind speed, and wake effects for streamlined structures (Petersen and Guerra, 2018). As mentioned previously, the PRIME model assumes all structures are rectangular. AERMOD is not able to properly characterize streamlined structures such as storage tanks and cooling towers. A wind tunnel study conducted by Petersen (2014) shows that dispersion is reduced in the wake of streamlined structures and that AERMOD may underpredict ground-level concentrations when these structures are modeled as rectangular buildings. In addition to new formulations for dispersion, PRIME2 has proposed separate formulations for rectangular and streamlined structures.

Next Steps

EPA plans to release a new version of AERMOD in the summer of 2019, prior to the 12th Conference on Air Quality Models. The release will include the ORD and PRIME2 building downwash alpha options summarized above. Once the source code is finalized and released, EPA will begin thorough testing and performance evaluations of the individual and combined effects of the alpha options. Likewise, EPA anticipates the user community will independently test and evaluate the performance of the new alpha options and provide feedback in preparation for the 12th Conference on Air Quality Models. EPA anticipates some combination of the alpha options will be identified for promotion to a single beta option, based on the results of EPA and independent evaluations. As a beta option, these improvements to building downwash will be staged for the next update to the *Guideline* at which time they will become part of the formulation of the regulatory version of AERMOD.

Future Work

Collaboration continues between AQMG, ORD, and PRIME2. Future research efforts include improvements to the plume rise calculations when subject to downwash and characterization of the lateral shift of the plume that occurs on the lee side of a building angled to the wind.

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