Issues Related to Building Downwash in AERMOD

Overview

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; Petersen et al., 2017).

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, for 36 wind directions (every 10-degrees) 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.

In addition to the limitation of the PRIME downwash model to treat the effects of more than a single structure, the effective building parameters generated by BPIPPRM that are input to AERMOD have come into question. A separate white paper on the topic the effective building parameters derived by BPIPPRM has been developed.

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

The next section summarizes some of the relevant peer-reviewed research on the effects of building downwash and specific issues related to PRIME that has been published since the promulgation of AERMOD in 2005.

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 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 directly downwind of the source (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 for 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

[1] Translation: Operational Meteorological Air Quality Model

building. Lateral dispersion increases with increased building width. In general, for the cases studied, 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.

Monbureau et al., 2018

A number of recent publications (e.g. Perry et al., 2016, Oleson, et al, 2009, Petersen et al., 2017, Schulman and Scire, 2012 and others) have demonstrated weaknesses in the performance of the AERMOD/PRIME model for building downwash applications. This paper discusses three proposed improvements to the AERMOD downwash algorithms (and one to its building preprocessor) that are primarily based on a series of wind tunnel experiments (Perry et al., 2016) and computational fluid dynamics simulations (Foroutan et al, 2018) involving a variety of rectangular building dimensions, stack locations and heights and wind angles. The changes involve 1) removing a discontinuity between the plume spread within the cavity region and the far wake region, 2) having the model compute the effective wind speed for calculating dispersion in the building wake (as done for plumes elsewhere in the model code) instead of using the wind speed at stack height, and 3) establishing the maximum turbulence intensity value of 0.07 as suggested by Weil (1996) rather than the value of 0.06 originally selected for AERMOD/PRIME to match the dispersion within the ISCST model. Finally, an alternative method for defining the effective building length for rectangular buildings at oblique wind angles was suggested. Rather than basing this dimension on the extremities of the building corners as currently done in the building preprocessor, the alternative is to select the dimension defined by the path that an air parcel would travel over the building providing a much more realistic effective building and a building wake more appropriated for the rotated structure.

After implementing all four model changes, a comparison with the variety of wind tunnel simulations showed a significant improvement in most cases with the overall fractional bias and normalized mean square error of maximum ground level concentrations cut approximately in half.

Petersen and Guerra, 2018

Petersen et al. (2017) documented several, what they described as, theoretical flaws in the AERMOD/PRIME algorithms that may account for model overpredictions of ground-level concentrations for certain building source configurations. Based on this previous work, an industry funded research study group (PRIME2) was initiated to advance the scientific understanding of building downwash, develop corrections to the noted problems and incorporate them into the code, expand the structure types from solid rectangles to include smooth and porous buildings and to document and evaluate the model formulations. Additionally, the PRIME2 committee is collaborating with both the research and regulatory sides of EPA on building downwash issues.

The paper presents the results from a new wind-tunnel study of wind speeds and turbulence intensity downwind of various solid and streamlined structures. Based on these measurements and a previous wind-tunnel data of flow and turbulence around rectangular buildings (Snyder and Lawson, 1994; Snyder, 2005), new equations were developed to estimate the velocity deficit and turbulence intensity enhancement in the building wake as a function of downwind distance, height, building shape and approach flow turbulence intensity and upwind surface roughness. Comparisons of new vertical and lateral turbulence intensity equations against the wind tunnel observations showed very good agreement. Finally, as expected, the maximum velocity deficit downwind of the streamlined structures is lower than that for rectangular sharp-edge structures. This and several other important findings from the wind tunnel study are reported in the summary and conclusions of the paper.

Foroutan et al., 2018 (in press)

A computational fluid dynamics technique called embedded large eddy simulation (ELES) was demonstrated to provide realistic representations of the flow and concentration fields observed in the Perry et al. (2016) wind tunnel study. The simulations capture the complex flow and dispersion phenomena observed in the wind tunnel including the lateral shift in the plume for oblique winds to the building and the enhancement of the vertical lateral plume spread with increased building aspect ratio. The ELES simulations provide highly-resolved representations of these phenomena for further study of the wind fields induced by the presence of buildings and the resulting plume behavior.

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