DEVELOPMENT AND EVALUATION OF THE PRIME PLUME RISE AND BUILDING DOWNWASH MODEL

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1. INTRODUCTION

The Electric Power Research Institute (EPRI) sponsored a study to develop and evaluate new, improved plume rise and building downwash algorithms suitable for integration into air quality models. The downwash algorithms in the Industrial Source Complex (ISC3) model, currently recommended for regulatory application, were largely developed with data that represented neutral stability, moderate to high wind speeds, winds perpendicular to the building face, and non-buoyant or low buoyancy plumes. Some of the limitations of the ISC3 downwash algorithms are (1) the location of the stack is not considered (if the stack is determined to be within the general region of influence of the building, the stack is always treated as though it were at the center of the lee wall of the building), (2) streamline deflection is not considered (ascent of the mean streamlines upwind of and over the building and descent in the lee of buildings), (3) there are no effects on plume rise due to the velocity deficit in the wake or vertical wind speed shear, (4) there is no linkage between plume material captured by the near wake and far wake concentrations, (5) there are discontinuities at the interface between the two downwash algorithms, (6) there are no wind direction effects for squat buildings, and (7) large concentrations predicted during light wind speed, stable conditions that are not supported by observations.

Proper treatment of all of the above factors are considered essential characteristics for an improved building downwash model. This paper summarizes some of the data used to develop the Plume Rise Model Enhancements (PRIME) model, a description of the new algorithms in the model, and the results of comparisons with field and wind-tunnel observations.

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2. WIND-TUNNEL AND FIELD DATA

A significant portion of the effort was directed towards measuring flow fields and plume behavior near buildings, which proved valuable for model development. Fluid modeling simulations were conducted at the U.S. Environmental Protection Agency Meteorological Wind Tunnel (Snyder, 1992 and Snyder and Lawson, 1993) and at the Monash University Wind Tunnel (Melbourne and Taylor, 1994). The U.S. EPA experiments provided concentration and flow field measurements for several generic building and source configurations. Some of the findings from these studies were presented by Snyder(1993) and Snyder and Lawson(1994), which provided detailed illustrations of the mean streamlines near buildings of different shapes and for different approach angles. They observed strong descent of the mean streamlines in the lee of the building. The trajectory of plumes followed different paths and were subject to different dispersion influences, depending on the exact position of the stack within the downwind wake.

A field study was conducted at the Jersey Central Power and Light Company Sayreville Generating Station in Sayreville, NJ, about 25 miles southwest of New York City, from 10 February to 5 March 1994. Meteorological measurements of wind speed and direction, wind turbulence, temperature, humidity, and short-wave and long-wave radiation were made by scientists from the National Center for Atmospheric Research using the ASTER facility and four instrumented 10-m towers (Oncley, 1994). A mobile, 1.06 micron wavelength Mark IX lidar system, operated by SRI International scientists (Kaiser, et al., 1994), collected back scatter data from the particulate plumes released by both a combustion turbine and a steam boiler with short stacks. The spatial resolution obtained was about 0.1 degrees in elevation and 1.5 m along the pulse. For lidar-to-plume distances of 800 m or less, the vertical resolution was better than 1.4 m. The data were processed to obtain one hour average centroid and variances for the composite plume images.

The steam boiler plume was observed to descend downwind of the boiler house during two high wind speed events. The slope of the descent was greatest on the day when the wind was oriented nearly 45 degrees to the face of the steam boiler building, instead of perpendicular to the building. The wind speed and boiler operation were nearly identical on both days. The plume rise from the combustion turbine was too high above the turbine roof to be significantly affected by the descending flow induced by nearby structures.

In addition to the wind-tunnel and field data, three-dimensional numerical modeling, using a finite element turbulence model, was conducted by Washington State University to provide a numerical laboratory for other building shapes and orientations. Comparisons of the numerical model simulations with the wind-tunnel observations showed similar velocity vectors, but a larger recirculation zone. (Brzoska, Stock and Lamb, 1996).

3. OVERVIEW OF THE PRIME MODEL

The central approach used in PRIME is to explicitly treat the trajectory of the plume near the building, and to use the position of the plume relative to the building to calculate interactions with the building wake. PRIME calculates the local slope of the mean streamlines as a function of projected building shape, and coupled with a numerical plume rise model, determines the change in plume centerline location with downwind distance. This incorporates the descent of the air containing the plume material, and rise of the plume relative to the streamlines due to buoyancy or momentum effects.

3.1 _Cavity and Wake Dimensions_

The height of the recirculation cavity above the building roof and whether the cavity reattaches to the roof follow Wilson (1979). The formulas are based on a scale length $R=B_S^{2/3}B_L^{2/3}$, where B_S is the smaller of the height or the width and B_L is the larger. The length of the downwind recirculation cavity (near wake) is taken from Fackrell (1984) and is a function of the building height, width and length. The mean envelope of the cavity boundary was fitted as an ellipse. The dimensions of the cavity were compared with the EPA wind-tunnel data for many different building shapes and found to agree quite closely. The wake height and width increase with downwind distance raised to the one-third power. This formulation is a blend of Wilson (1979) over the building and Weil (1996) downwind of the building.

3.2 _Mean Streamline Slope_

The formulation for the slope of the mean streamlines is based on the location and maximum height of the roof-top recirculation cavity, the length of the downwind recirculation cavity and the building length scale R. In general, the mean streamlines follow the shape of the near wake. For example, for a very wide building the descent of the mean streamlines is not as steep as for a narrow building of the same height and length. For two buildings of the same height and width, the descent of the mean streamlines is steeper for the building with the shorter length. The magnitude of the descent changes with wind direction as the projected building width and length change. For most cases in PRIME, the streamline descent is greater for 45 degree angles to the building face than for perpendicular winds. Comparisons of the predicted slopes of the mean streamlines with the streamlines presented by Snyder and Lawson (1994) for ten different building shapes showed excellent agreement and were reported in Schulman and Scire (1996).

3.3 _Plume Rise_

The PRIME plume rise is computed using a numerical solution of the mass, energy and momentum conservation laws (Zhang and Ghoniem, 1993). The model allows arbitrary ambient temperature stratification, arbitrary uni-directional wind shear, and arbitrary initial plume size. It includes radiative heat losses and can be run optionally in a non-Boussinesq mode. The implementation of the model in PRIME allows for streamline ascent/descent effects to be considered, as well as the enhanced dilution due to building induced turbulence. A key feature of the model is its ability to include vertical wind shear effects, which are important for many buoyant releases from short stacks. Additionally, the wind speed deficit induced by the building is modified as a function of downwind distance from the building. The deficit also leads to increased plume rise from short stacks.

3.4 *Dispersion Coefficients*

PRIME dispersion is based on the approach of Weil (1996). Enhanced turbulence intensity and velocity deficit values are calculated within the wake region. These values are a maximum at the lee wall of the building and decay with the two-thirds power downwind. Ambient turbulence intensity is inferred from the Briggs dispersion coefficient formulas for rural and urban as reported in Gifford (1976). If the plume is released upwind of the wake, the plume initially grows at the ambient rate. At the point that the plume intercepts the wake, a probability density function model is used for plume dispersion over a distance equal to the length of the near wake, and an eddy diffusivity model for plume growth is used beyond. When the turbulence intensity within the wake has decayed to the ambient rate, a virtual source technique is used to transition to the ISC3 dispersion curves. For an unstable ambient stability, or if the plume is intercepted by the wake several building heights downwind, the building effects on plume dispersion may be small and short-lived. Nearer to the building or with neutral and stable approach flows the building effects will be larger.

As observed in wind-tunnel, both the horizontal and vertical dispersion coefficients are enhanced in the building wake. This virtually eliminates the suspiciously large predictions by ISC3 during light wind speed, stable conditions which are caused by only enhancing the vertical dispersion coefficient when the stack height is more than 20% higher than the building height.

3.5 *Near/Far Wake Concentrations*

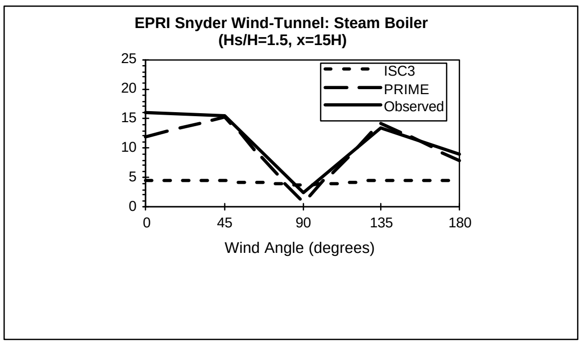
The ISC3 model is only valid for the far wake (defined in ISC as beyond the lesser of three building heights or building widths). A separate model, SCREEN3, is recommended by EPA for near wake concentrations. PRIME predicts concentrations in both the near and far wakes. The fraction of the plume captured by the near wake is well-mixed within the near wake following Wilson and Britter (1982). That plume mass is then re-emitted to the far wake as a volume source and added to the uncaptured primary plume. A transition zone between the near and far wakes is used to represent the unsteadiness of the near wake/far wake interface. In the transition zone, the concentrations are calculated as the sum of the uncaptured primary plume contribution plus a combination of the near wake concentration and the volume source concentration.

4. COMPARISON WITH OBSERVATIONS

PRIME was evaluated with wind-tunnel data from Snyder (1992), collected as part of this project, and Thompson (1993), made available by the author. In addition, other data sets were made available to the model developers, and PRIME has been evaluated with the data collected at the Bowline Point Generating Station and the EPA Alaska North Slope field study.

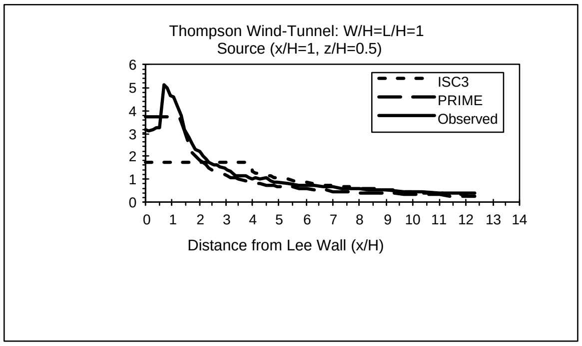
4.1 *Snyder Wind-Tunnel Data*

These data include systematic variations of stack to building height ratios, ratios of exhaust speeds to wind speeds, wind angle, Froude number and stack location for both a generic steam boiler and combustion turbine. Figure 1 shows the comparison of PRIME and ISC3 to data for a steam boiler with stack to building height ratio of 1.5 at 15 building heights downwind for 5 different wind angles to the building face. The building width is twice the height and 2.5 times the length with a direction of zero degrees defined as perpendicular to the wider horizontal dimension. The stack is downwind of the building for this direction. PRIME matches the concentration trends with wind direction. The lowest concentrations occur with winds perpendicular to the shorter dimension. The stack is to the side of the building for this direction. ISC3 shows almost no variation with wind direction because the building is squat for most directions.



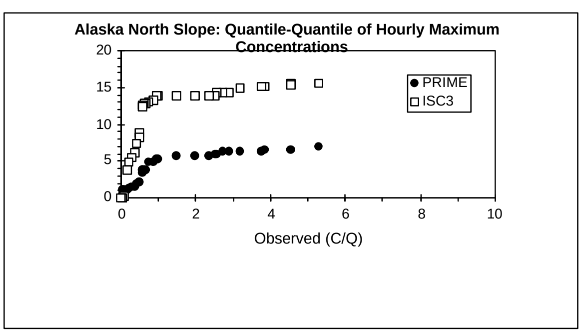
4.2 *Thompson Wind-Tunnel Data*

These data consist of non-buoyant, zero-momentum releases upwind of and in the near and far wakes of four different building shapes. Figure 2 shows the comparison of PRIME and ISC3 to data for a source in the downwind cavity at half the building height above the ground. SCREEN3 was run for the cavity concentrations. PRIME shows better agreement in the cavity. Both models do well in matching the downwind concentrations.



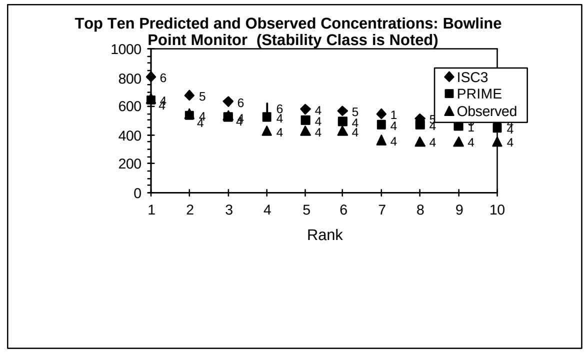
4.3 *Alaska North Slope*

A field study was conducted near Prudhoe Bay (Guenther, Lamb and Allwine, 1989) for a high buoyancy, high momentum combustion turbine with a stack to building height ratio of 1.15. Thirty-eight hours of tracer data and onsite meteorological data were collected during high wind conditions over a 7 day period. Figure 3 shows that PRIME shows better agreement than ISC3 for the largest concentrations, but both models over predict for the smaller observed values.



4.4 *Bowline Point*

One-half year of measured meteorological, emissions and concentration data for a 1200 MW power plant were used to evaluate ISC3 and PRIME. The plant has two identical stacks that are 1.33 times the building height. Figure 4 shows the ten highest observed and predicted concentrations at the monitor with the largest observed values. Both models capture the high observations well, but also tend to overestimate the tenth highest value. However, only PRIME correctly matches the neutral stability conditions of the observations. ISC3 predicts the highest concentrations to occur during stable conditions when much lower values were observed.



5. SUMMARY

The PRIME model includes several advances in modeling building downwash effects including enhanced dispersion in the wake, reduced plume rise due to streamline deflection and increased turbulence, and a continuous treatment of the near and far wakes. All of these effects consider the location of the plume within the wake. Comparisons of the model with wind-tunnel and field data have shown improved performance over the current ISC3 model. The model is implemented within the ISC3 model code, but can be implemented in other refined or screening air quality models.

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