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Evaluation of a Fast-Response Urban Wind Model – Comparison to Single-Building Wind-Tunnel Data

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Introduction

Prediction of the 3-dimensional flow field around buildings and other obstacles is important for a number of applications, including urban air quality studies, the tracking of plumes from accidental releases of toxic air contaminants, indoor/outdoor air pollution problems, and thermal comfort assessments. Various types of computational fluid dynamics (CFD) models have been used for determining the flow fields around buildings (e.g., Reisner et al., 1998; Eichhorn et al., 1988). Comparisons to measurements show that these models work reasonably well for the most part (e.g., Ehrhard et al., 2000; Johnson and Hunter, 1998; Murakami, 1997). However, CFD models are computationally intensive and for some applications turn-around time is of the essence. For example, planning and assessment studies in which hundreds of cases must be analyzed or emergency response scenarios in which plume transport must be computed quickly.

Several fast-response dispersion models of varying levels of fidelity have been developed to explicitly account for the effects of a single building or groups of buildings (e.g., UDM – Hall et al. (2000), NRC -Ramsdell and Fosmire (1995), CBP-3 - Yamartino and Wiegand (1986), APRAC - Dabberdt et al. (1973)). Although a few of these models include the Hotchkiss and Harlow (1973) analytical solution for potential flow in a notch to describe the velocity field within an urban canyon, in general, these models do not explicitly compute the velocity field around groups of buildings. The EPA PRIME model (Schulman et al., 2000) has been empirically derived to provide streamlines around a single isolated building. A potential flow model called MIDAS-AT has been advertised for dispersion applications in urban areas (http://www.plg-ec.com/), however, the authors have not been able to obtain reports or open-literature publications. In principle, a potential flow model can produce velocity fields around groups of buildings, but with the restriction that the flow must be irrotational.

Röckle (1990) developed a diagnostic mass consistent wind model for computing the 3D flow field around isolated buildings and groups of buildings. Like the PRIME code, the model utilizes empirical algorithms for determining initial wind fields in the cavity, wake, and upstream recirculation zones for single buildings, but it also includes algorithms for velocity fields in between buildings. A mass consistent wind field is then produced similar to the approach used in traditional diagnostic wind modeling (e.g., Sherman, 1978), except that special treatment of boundary conditions is needed at building walls. The computed wind field is not restricted to being irrotational.

For a street intersection defined by four adjacent courtyards, Röckle *et al*. (1998) showed reasonable agreement between model-computed wind fields and wind-tunnel measurements for various inflow wind angles. Gross (1997) compared concentrations produced using the model with experimental measurements. Kaplan and Dinar (1996) qualitatively compared the model solutions to CFD model results for flow around two and three buildings and to wind-tunnel measurements of concentration on street canyon walls. Using a wind-tunnel study of an industrial complex, Röckle (1990) found that the model-computed wind directions and wind speed agreed fairly well at several points within the complex for various inflow wind directions. Surprisingly, the urban diagnostic wind model approach has not been extensively tested for the single building case. We have found one example, in which Gross et al. (1994) compared turbulent intensity predictions with a few measurements made downwind of a cube. To help resolve this deficiency, in this paper we compare model results to centerline velocities measured in the USEPA meteorological wind tunnel (Snyder and Lawson, 1994) for rectilinear buildings of varying width, height, and downwind length with a prevailing wind normal to the building face. We begin with a short description of our implementation of the Röckle model.

Model description

Our fast response urban wind model, QWIC-URB, is based on the dissertation of Röckle (1990). In this model, an initial wind field is prescribed based on an incident flow and superimposed on this are various time-averaged flow effects associated with the buildings. The assumptions built into the parameterizations require self-similar behavior for various obstacle length scales (see Fig. 1). The size of the upwind cavity, the lee-side cavity and the far wake zone are parameterized, in addition to the velocity field within these zones. Many of the relationships are found in Hosker (1984). The model does not, however, address the rooftop or sidewall recirculation zones. The final 3D velocity field is obtained by forcing this velocity field to be mass consistent. The velocities are forced to zero at grid points within buildings. We use the same empirical logic as Röckle (1990) (and later Kaplan and Dinar, 1996), however, our numerical implementation is slightly different.

The length of the upwind cavity, L_F, is given as a function of the building height (H) and cross-stream width (W). The initial velocity in the upwind cavity zone is specified as zero. The shape of the cavity is an ellipsoid and varies with H and W. The downwind cavity length, L_R, is given by Fackrell's (1984) parameterization which is a function of H, W, and downwind length of the building L. The length of the far wake zone is approximated as $3L_R$. The lee-side cavity and far wake are approximated by ellipsoids and are functions of H and W. The longitudinal component of the velocity is specified within these two zones using formulae that depend on the distance to the back side of the building and the length of the cavity (or wake) at the particular height of calculation. The velocity profile in regions unaffected by buildings is given by a power-law profile with an exponent of 0.16 in order to match the work of Snyder and Lawson (1994).

Experimental Description

Snyder and Lawson (1994) performed pulsed-wire anemometer experiments around building obstacles in a deep simulated neutral atmospheric boundary layer in the USEPA Meteorological Wind Tunnel. The wind-tunnel is of the open-return type with a test section 3.7 m wide, 2.1 m high and 18.3 m long. Centerline mean and turbulence velocity data was obtained at various heights both upwind and downwind of the obstacles. For this study, we have made comparisons with a cubical building (H = W = L), a wide building (W = 4H, H=L), a tall building (H = 2W, L=W), and a long building (L = 4H, H=W) all with the inflow perpendicular to the front face of the building.

Model-Data Comparisons

Figures 2, 3, 4, and 5 show model-data comparisons of the velocity fields for the four different cases. It is apparent that although the model produces some of the flow features correctly, there are significant differences. For all cases we found that 1) the jet measured over the upstream edge of the building is stronger than computed by the model, 2) the upstream extent of the front side recirculation zone is overpredicted, 3) no rooftop recirculation or slowing down of the wind was computed on the rooftop, and 4) the magnitude of the winds in the wake region were overpredicted. Although difficult to determine exactly due to the sparseness of the data, the size of the downstream cavity is reasonably predicted in all four cases. In addition, the stagnation point on the upwind building face was well predicted for each case. Comparison of significant flow parameters are given in Table 1.

Table 1 – Building flow parameters: model computations vs. wind-tunnel data

Building type	upstream reattachment point		upstream stagnation point		downstream reattachment point		downstream vortex center height	
	model	data	model	data	model	data	model	data
Cube (H=W=L)	-1.0 H	-0.25-0.5 H	0.8 H	0.6-0.8 H	1.1 H	1.0-1.5 H	0.8-0.9 H	0.5-0.8 H
Wide (W=4H)	-1.75 H	-0.5-1.0 H	0.8 H	0.6-0.8 H	2.8 H	3.0-3.5 H	0.8-1.0 H	0.7-0.9 H
Tall (H=2W)	-0.5 H	-0.1-0.25 H	0.8 H	0.5-0.75 H	0.75 H	0.75 H	0.9-1.0 H	0.75-1.0 H
Long (L=4H)	-1.0 H	-0.25-0.5 H	0.8 H	0.5-0.75 H	0.7-0.8 H	1.0-2.0 H	0.8-1.0 H	0.5-0.8 H

*upstream and downstream reattachment points measured from upwind and downwind building faces, respectively.

Summary & Conclusions

Centerline velocity measurements obtained around single buildings in a wind-tunnel were used to test the Röckle (1990) model. Some differences were found between model-computed and measured flow fields, especially in the upstream and rooftop recirculation zones. We intend to modify our version of the Röckle model (QWIC-URB) to better parameterize effects. However, we first need to perform further tests varying grid size and various numerical parameters. In addition, we recently implemented an oblique wind angle capability for the single building case and comparisons to data will be performed in the near future.

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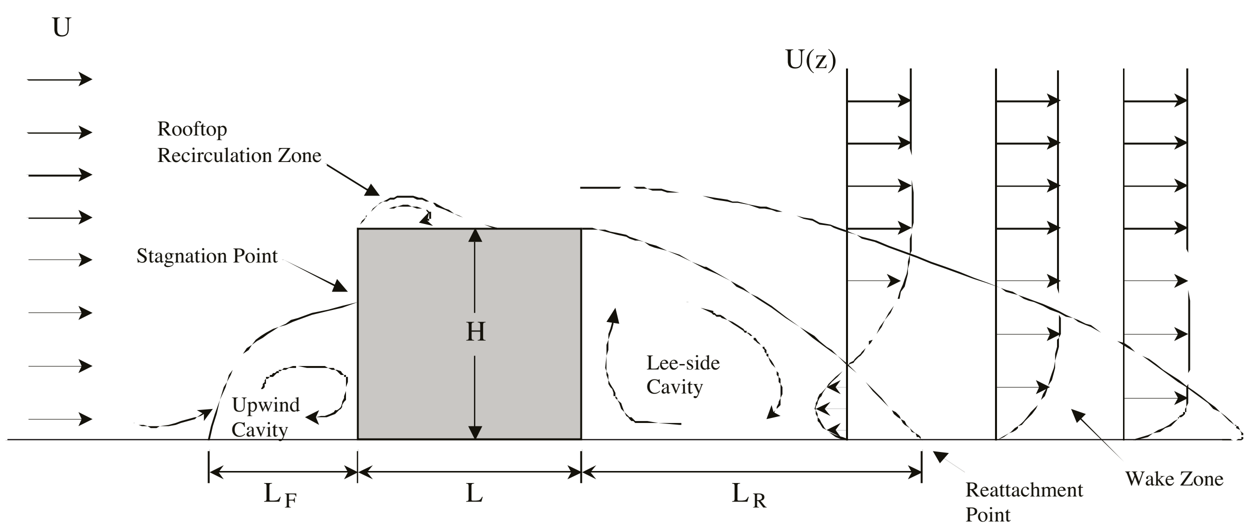

Figure 1. Schematic of the various flow phenomena associated with flow around a building.

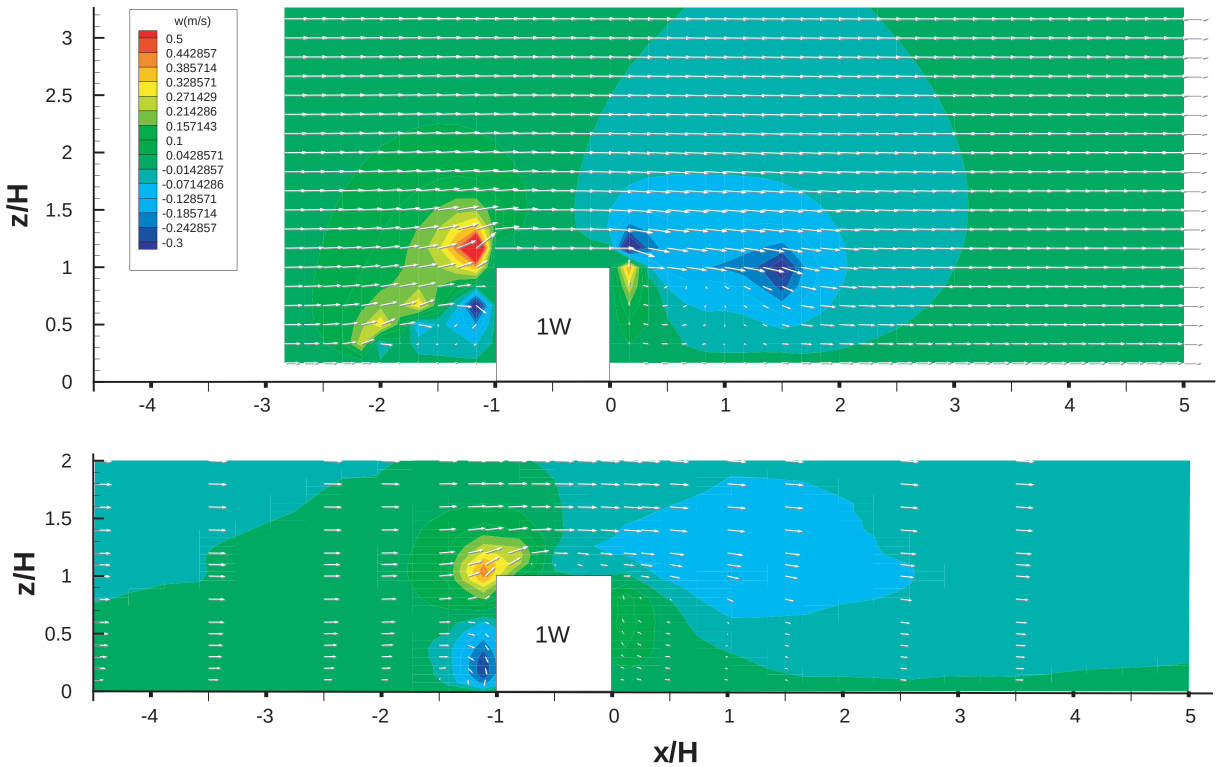

Figure 2. Model (top) vs. measurements (bottom) for cubical building (H=W=L).

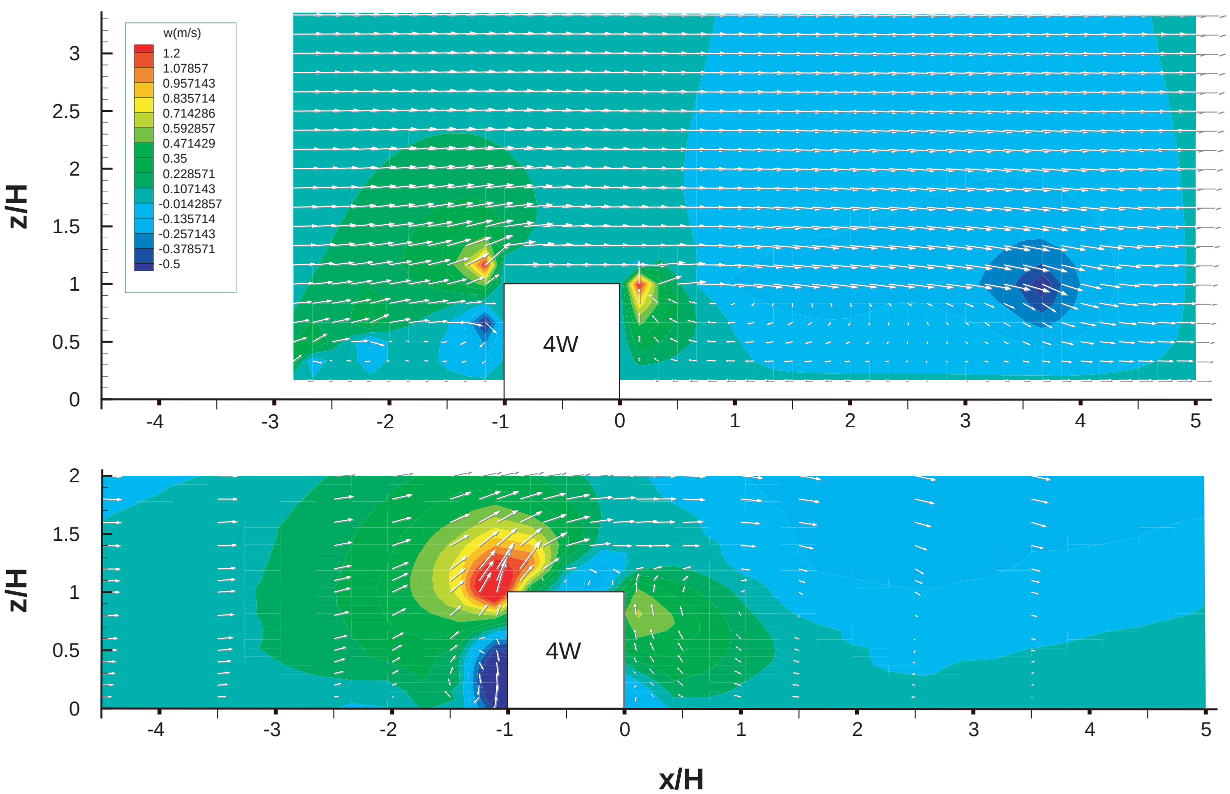

Figure 3. Model (top) vs. measurements (bottom) for wide building (W=4H=4L).

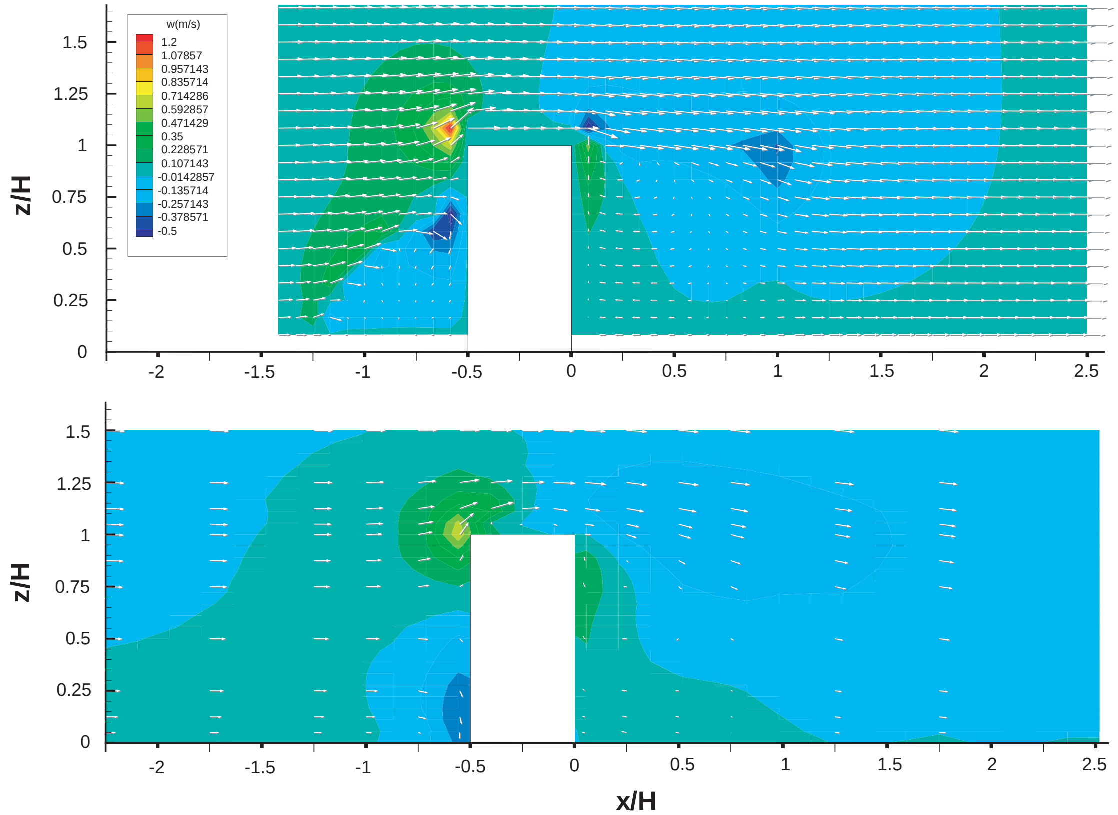

Figure 4. Model (top) vs. measurements (bottom) for tall building (H=2W=2L).

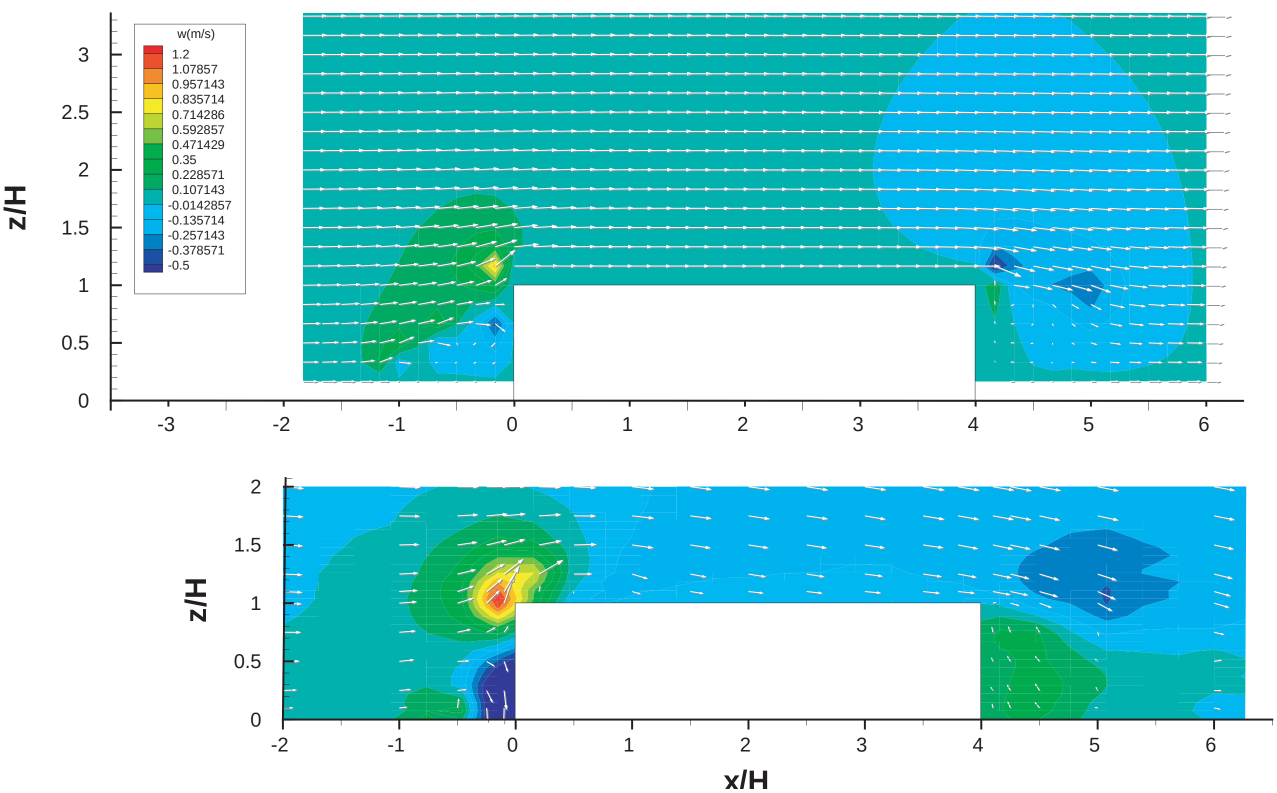

Figure 5. Model (top) vs. measurements (bottom) for long building (L=4H=4W).