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Testing of a Far-wake Parameterization for a Fast Response Urban Wind Model

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1. Introduction

The Quick Urban & Industrial Complex (QUIC) dispersion modeling system has been developed to rapidly provide 3D wind and concentration fields in cities. The QUIC dispersion model is comprised of a wind model called QUIC-URB, a Lagrangian dispersion model called QUIC-PLUME, and a graphical user interface called QUIC-GUI. The fast response 3D urban wind model QUIC-URB explicitly solves for the flow field around buildings using a suite of empirical parameterizations and mass conservation (Pardyjak, 2003). The technique is based on the work of Röckle (1990, 1998) and Kaplan & Dinar (1996).

The flow structure around buildings is complex in nature. Previous QUIC-URB model evaluations against single- and multi-building wind-tunnel data sets have shown weaknesses in several of the standard parameterizations (Kastner-Klein, 2003; Pardyjak and Brown, 2002; Pardyjak and Brown, 2001). These evaluations revealed some weaknesses in the winds produced in the wake region. In the standard QUIC-URB model, an ellipsoidal envelope of velocity deficit region is defined behind the building, which is confined to the width of the building (see Fig. 1). After mass conservation, the model-computed winds reveal overly strong mean velocity gradients confined to a narrow region behind the building at the interface between the wake region and the ambient flow. This step-change in velocity observed at the wake-ambient flow interface is due to the lack of momentum diffusion in the QUIC-URB model. Since QUIC-URB does not solve the momentum equations, there is no mechanism in the model that accounts for the diffusion of wake momentum. To improve the wind field calculations, the wake parameterization needs to be modified to approximate the effect of momentum diffusion.

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To address this problem, two different algorithms – one for the horizontal direction and one for the vertical – based on the shelter model work of Taylor and Salmon (1993) have been implemented to account for the momentum diffusion in the wake. This shelter model employs a Gaussian-shaped envelope that extends beyond the width of the building in the wake region. In this paper, we will provide the details of the new wake parameterization scheme and then show comparisons to flow measurements obtained around building obstacles in a wind tunnel. We will show that the shelter model significantly improves the prediction of velocity distributions in the far wake.

2. The Original QUIC-URB Cavity and Wake Parameterization

A brief explanation of the existing QUIC-URB wake parameterization is given in this section. QUIC-URB uses the equations and parameters found in Röckle (1990) to define an ellipsoidal cavity (reversed flow) and wake (velocity deficit) region behind the building

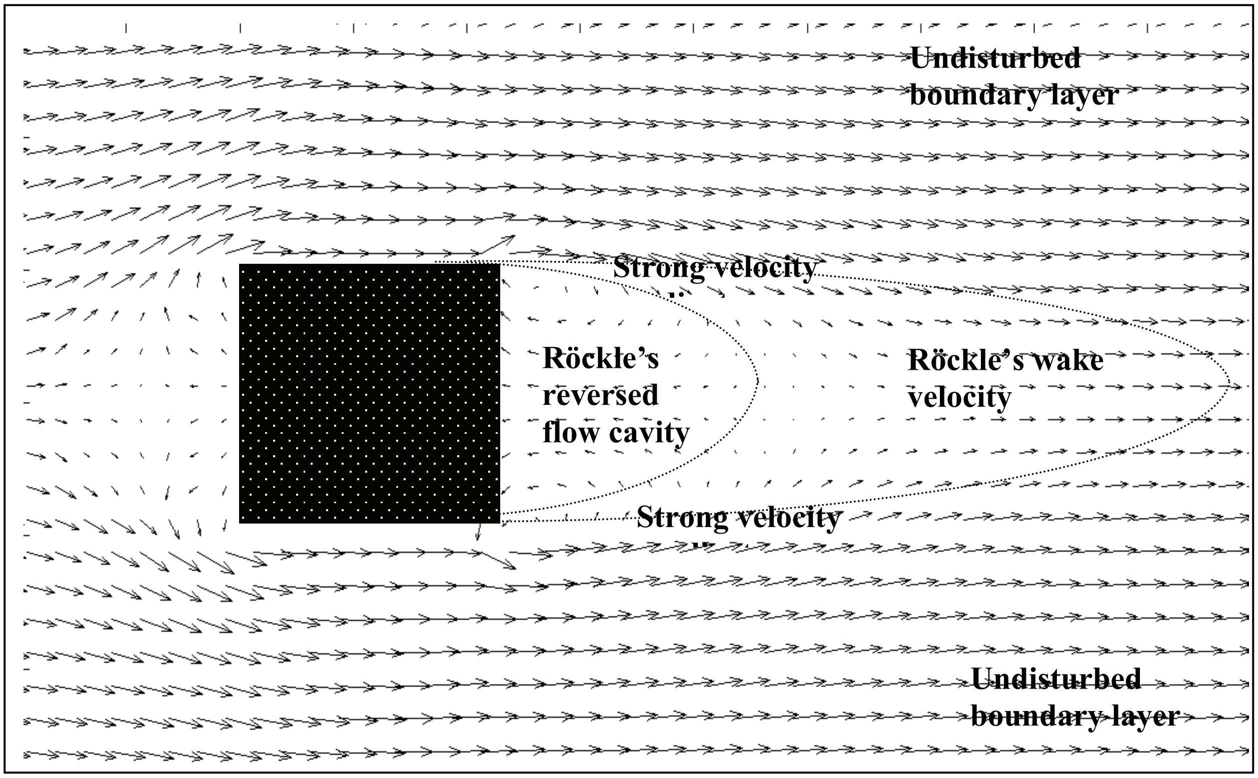

Figure 1. A schematic showing sharp velocity gradient regions at the interface of the standard QUIC-URB wake region and the undisturbed boundary layer flow.

(see Fig. 2). The downwind length of the cavity zone is defined by the distance to the reattachment point L_R from Röckle (1990),

$$\frac{L_R}{H} = \frac{1.8\frac{W}{H}}{\left(\frac{L}{H}\right)^{0.3}\left(1+0.24\frac{W}{H}\right)} \qquad (1)$$

where L, H, and W are the length, width, and height of the building, respectively. The length of the wake zone is assumed to extend approximately 3 cavity lengths (i.e., $3Lr$).

Röckle (1990) defined the initial velocity field in the reversed flow cavity region:

$$\frac{u(x,y,z)}{U(H)} = -\left(1-\left(\frac{x}{d(y,z)}\right)^2\right), \qquad (2)$$

where $u(x,y,z)$ is the velocity at point (x, y, z) in the cavity, $U(H)$ is the reference velocity at the height of the building, x is the distance from the building in the streamwise direction, and $d(y,z)$ is the length of the cavity in the streamwise direction at any (y,z). The cavity length d was defined by an ellipsoid shape and calculated as:

$$d(y,z) = L_R\sqrt{\left(1-\left(\frac{z}{H}\right)^2\right)\left(1-\left(\frac{y}{W}\right)^2\right)} - \frac{L}{2}. \qquad (3)$$

The velocity in the wake zone was defined as:

$$\frac{u(x,y,z)}{U(H)} = \left(1-\left(\frac{d(y,z)}{x}\right)^{1.5}\right). \qquad (4)$$

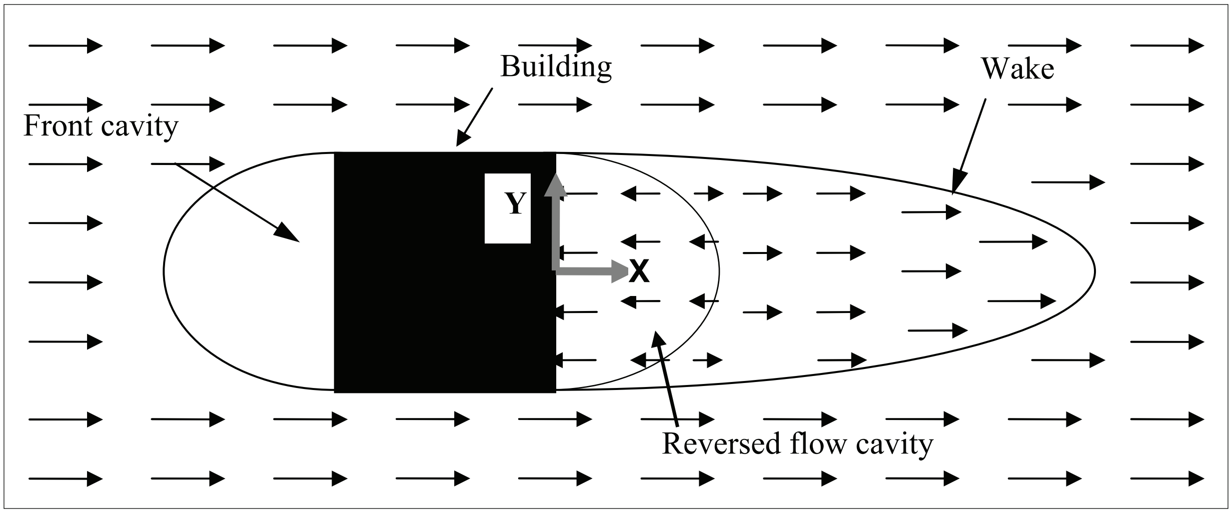

Figure 2. A plan view schematic of the original Röckle scheme showing the cavity and wake zones in a horizontal plane just above the ground.

The velocity outside the cavity and wake regions is defined by the upwind boundary-layer profile.

3. The New QUIC-URB Cavity and Wake Parameterization

To account for the diffusion of momentum outwards from the cavity and wake zones, two different algorithms for the initial wind field – one for the horizontal direction and one for the vertical – have been employed. These algorithms are applied to the initial wind field of QUIC-URB and the final 3-D velocity field is obtained by forcing this initial velocity field to be mass consistent.

3.1 Diffusing gradient in the horizontal direction

Experimental observations show that the velocity deficit in the wake varies with streamwise distance from the end of the building as $x^{-1/2}$ and with lateral distance from the building centerline as y. The velocity deficit in the horizontal plane in the building wake region was defined as:

$$u(x,y,z) = (U_{Ref\_hor} - U_z)\exp\left(-\eta^2\right) + U_z \ , \quad (5)$$

where U_{Ref_hor} is the velocity at the edge of the wake (see Eqns. (2) and (4)), U_z is the upstream boundary layer velocity at a height z, and η is the non-dimensional transverse coordinate defined by Taylor and Salmon (1993) as,

$$\eta = \left(\frac{y}{W}\right)\left(\frac{x}{H}\right)^{-1/2} . \quad (6)$$

The velocity at any point (x,y,z) is given by $u(x,y,z)$, which describes the velocity outside Röckle's wake region and merges the velocities exponentially between the wake and boundary-layer velocities at a given height (see Figs.3a and 3b).

3.2 Diffusing gradient in the vertical direction

Similar to the horizontal case, velocities at the edge of the Röckle's wake in the vertical are taken as reference velocities and are made to decay exponentially with height using the following mathematical formulation:

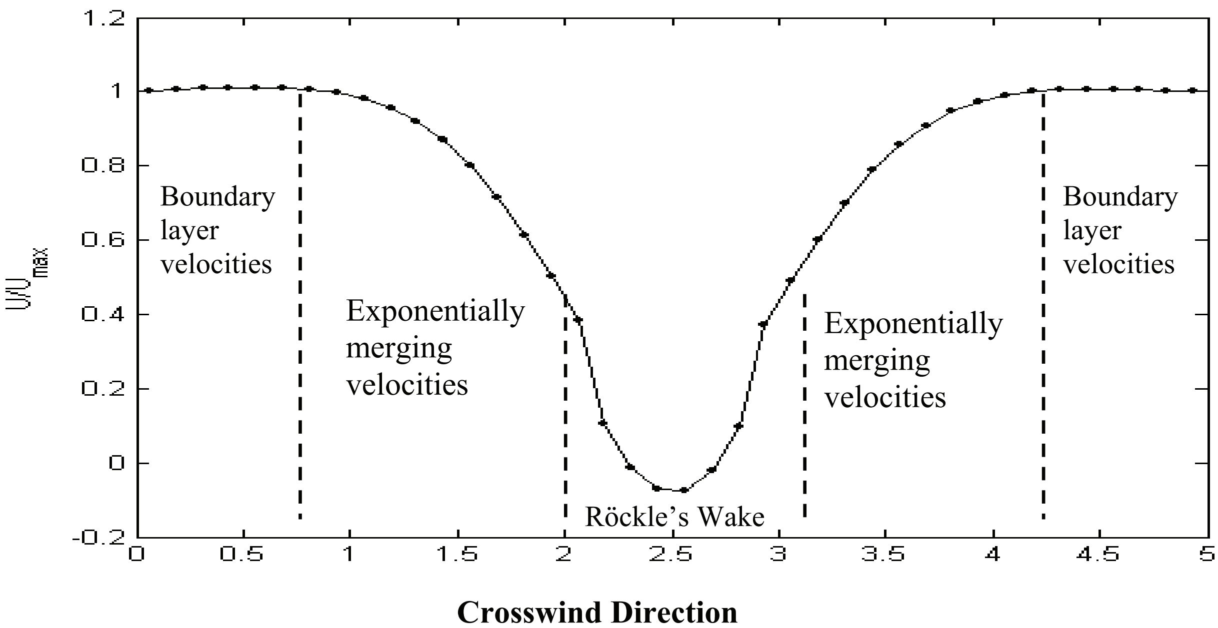

Figure 3a. A lateral profile of velocity behind a cubic building showing Röckle's wake velocities exponentially merging with the boundary-layer flow at x/H = 1 and z/H = 0.1.

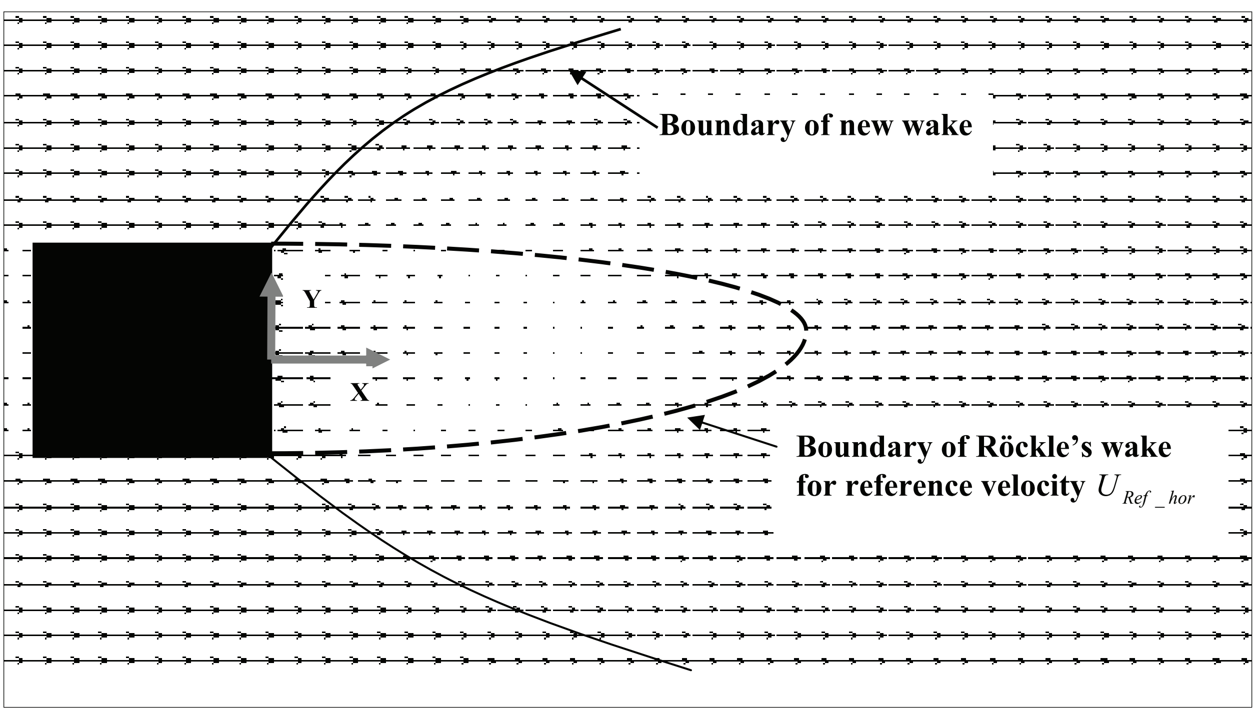

Figure 3b. Wind vectors in a horizontal plane showing the resultant wind field after applying the new wake scheme (but before applying mass conservation).

$$u(x,y,z) = (U_{Ref\_vert} - U_z)\exp\left(-\xi^{1.5}\right) + U_z \quad \ldots(7)$$

where U_{Ref_vert} is the velocity at the edge of the Röckle's wake in the vertical, U_z is the velocity at a height z in the undisturbed boundary layer, and the non-dimensional vertical coordinate is given by,

$$\xi = \left(\frac{Ht\_ellipse(x,y)}{z - Ht\_ellipse(x,y)}\right)^{-1/2}\left(\frac{x}{H}\right)^{-1/2} \qquad (8)$$

where the *Ht_ellipse* is the local height of the ellipse (see Figs. 4a and 4b).

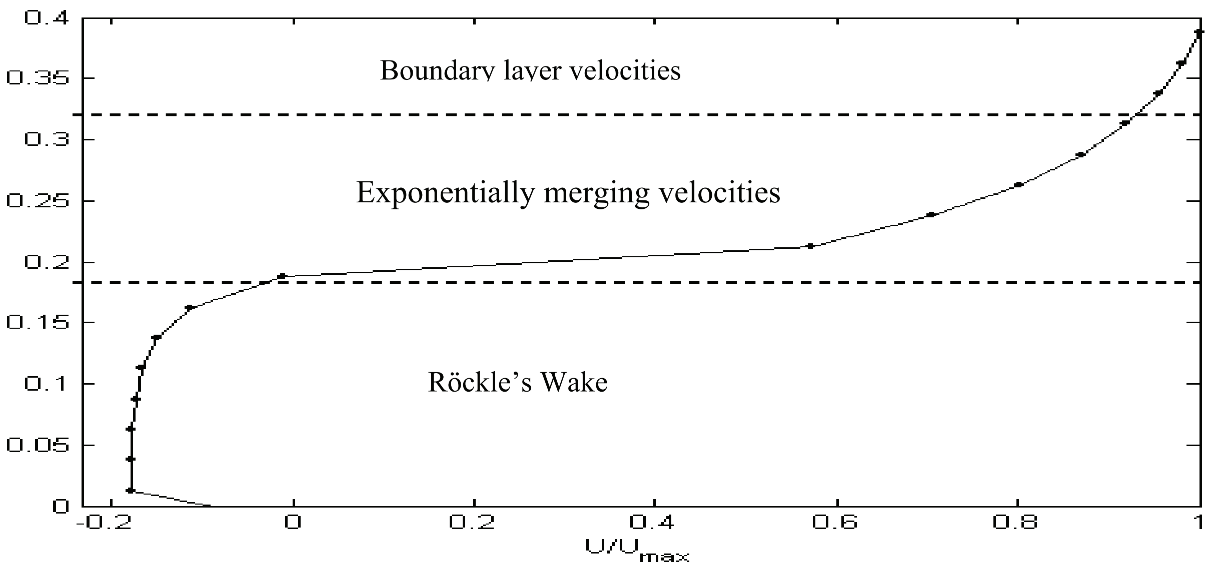

Figure 4a. A vertical profile of the centerline velocity behind a cubical building showing Röckle's wake velocities exponentially merging with the boundary-layer flow at x/H = 1.

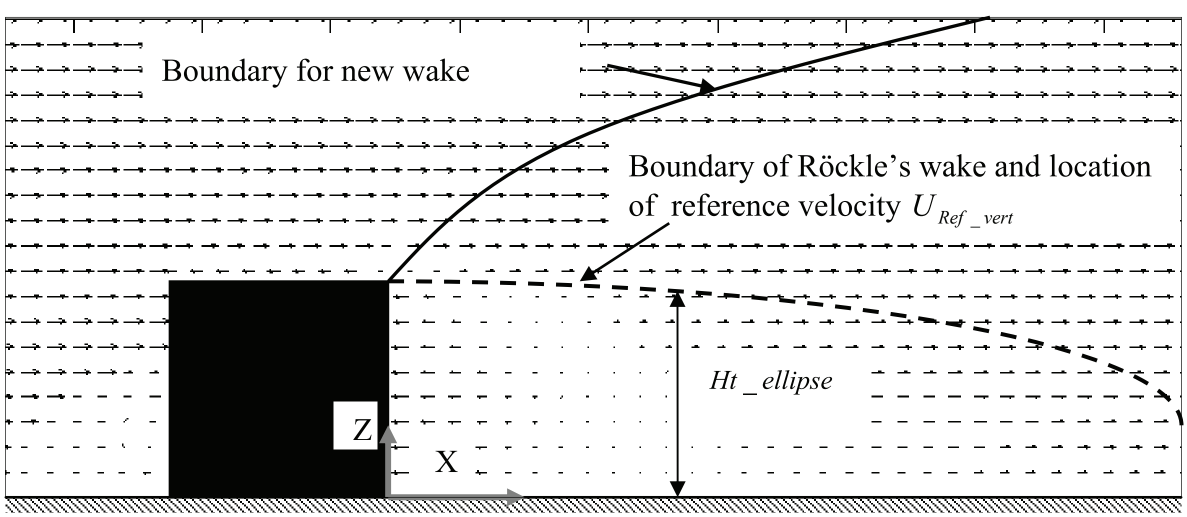

Figure 4b. Wind vectors in a vertical plane showing the resultant wind field after applying the new wake scheme (but before mass conservation has been applied).

4. Experimental Setup

The new wake scheme, based on the shelter model of Taylor and Salmon (1993), was tested against measurements made in a wind tunnel of the flow field in the vicinity of a variety of single isolated buildings. This data set, from Snyder and Lawson (1994), includes the velocity field around buildings of various dimensions in a fully turbulent boundary layer (1.8m deep) with the mean flow inflow profile described by a power-law with exponent 0.16. For the comparisons, the cases chosen were flow around a cubical building (L = W = H = 200 mm), a wide building (H = L = 200 mm, W = 2L) and a tall building (W = L = 200 mm, H = 2L). The Reynolds number based on the building height was about 34,682. A pulsed-wire anemometer (PWA) was employed to measure the velocity components in the vertical and longitudinal directions.

5. Results & Discussion

The result section is divided into three sections. In the first section, QUIC-URB wind fields using the original and the new modified wake scheme are compared to the wind measurements obtained around the cubical building. In the second and third sections, model output is compared to the measurements around a wide building and a tall building.

5.1 Isolated cube

For comparing the model with the experimental measurements, the normalized lateral and vertical velocity profiles ($U_{measured}/U_{max}$) are plotted at several distances downstream of the cube, where U_{max} is the velocity in the undisturbed flow.

5.1.1 Horizontal comparisons

Mean velocity profiles are compared along the crosswind direction at three downstream distances from the backside of the cube (X/H = 0.5, 1 and 1.5). Figure 5 shows the velocity comparison at X/H = 0.5. The new wake model clearly gives a better estimate of the transition of velocity from inside to outside Röckle's wake region as compared to the original scheme. The original wake model exhibits a sharp gradient in the velocity at the edge of Röckle's wake region. Both schemes slightly underpredict the magnitude of the reverse flow in the cavity region.

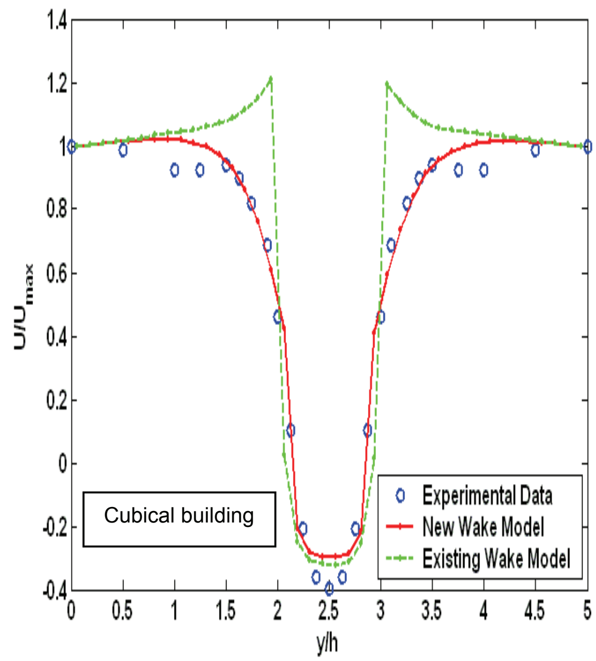

Figure 5. Comparison of model-computed and measured lateral profiles of velocity at X/H=0.5 and Z/H=0.1 for the new and original wake schemes.

Figure 6 shows the velocity profile comparison in the crosswind direction at X/H=1 downstream of the cubical building. Here also, the new wake model gives a better estimate of the velocity outside the Röckle's wake region but slightly over-predicts the velocities in the Röckle's reversed flow cavity. The original wake model shows a sharp increase in the velocity values (concentrated in a very small region) at the edge of Röckle's wake region. Also, the original wake model predicts the Röckle's reversed flow cavity velocities quite well.

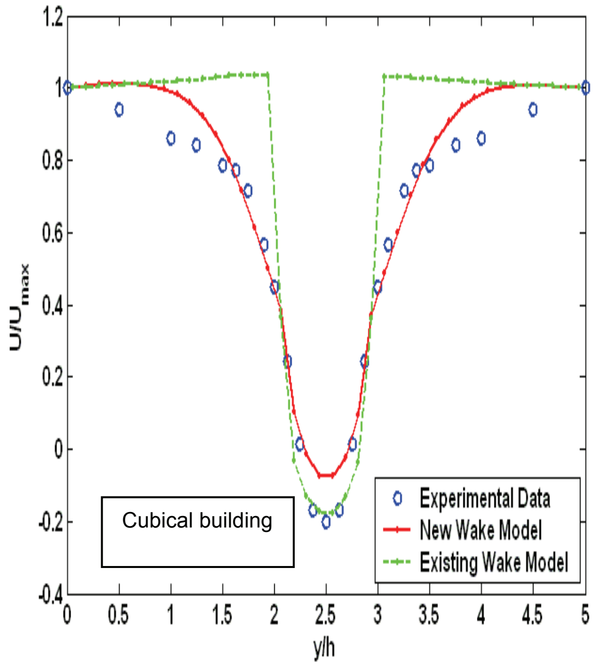

Figure 6. Comparison of model-computed and measured lateral profiles of velocity at X/H=1 and Z/H=0.1 for the new and original wake schemes.

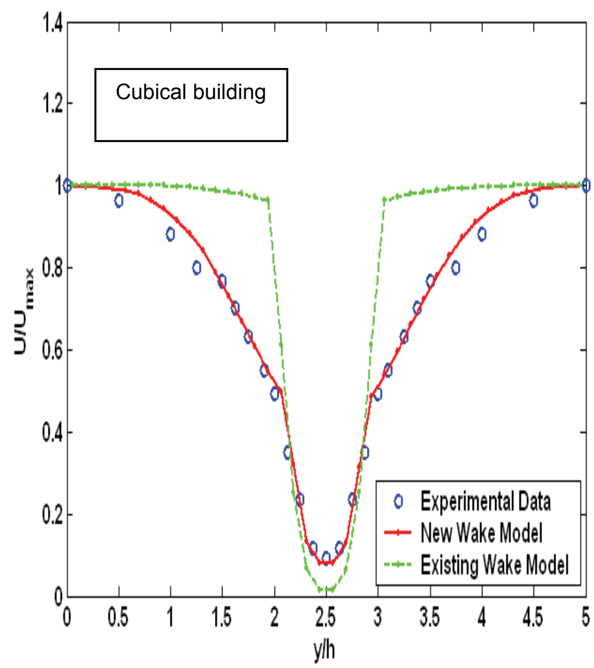

Figure 7. Comparison of model-computed and measured lateral profiles of velocity at X/H=1.5 and Z/H=0.1 for the new and original wake schemes.

Figure 7 shows the velocity data comparison in the crosswind direction at X/H=1.5 downstream of the building. The original wake model shows a sharp increase in the velocity values at the edge of the Röckle wake region. The new wake model gives a good estimate of the velocity magnitude outside the Röckle's wake region as well as predicts the velocities within the Röckle wake region quite well.

5.1.2 Vertical Comparisons

Mean velocity profiles are compared in the vertical direction at three downwind distances from the back edge of the building ($X/H =$ 0.5, 1 and 1.5). At $X/H = 0.5$, the new wake model gives a better estimate of how the velocity transitions to the ambient flow at rooftop as compared to the original scheme (Fig. 8). In both cases, the velocity gradient in the cavity region does not match the measured gradient.

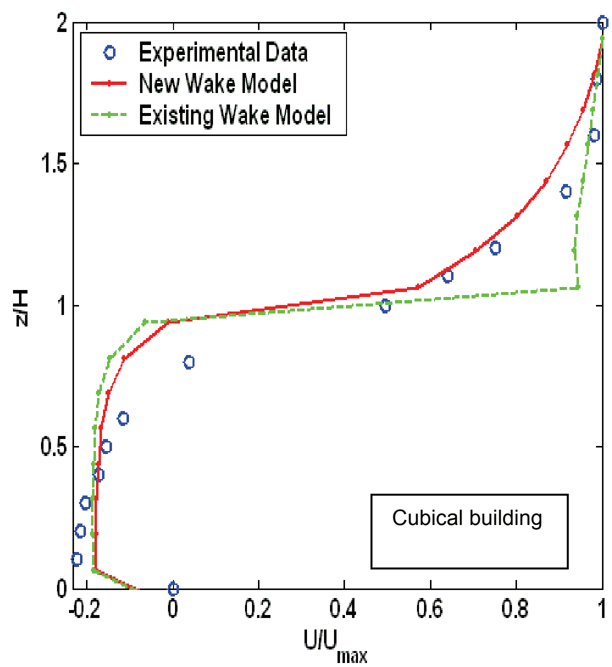

Figure 8. Comparison of model-computed and measured vertical profiles of velocity on the centerline at X/H=0.5 for the new and original wake schemes.

Figure 9 shows the comparison of the model output with the wind-tunnel measurements in the vertical direction at one building height downstream of the back edge of the building. Here also, the new wake model gives a better estimate of the velocity gradient at rooftop as compared to the original scheme which shows a kink in the profile. One can also see that the new scheme under predicts the reverse flow velocities in the lower half of the cavity, while the original scheme over predicts the reverse flow in the upper-half of the cavity.

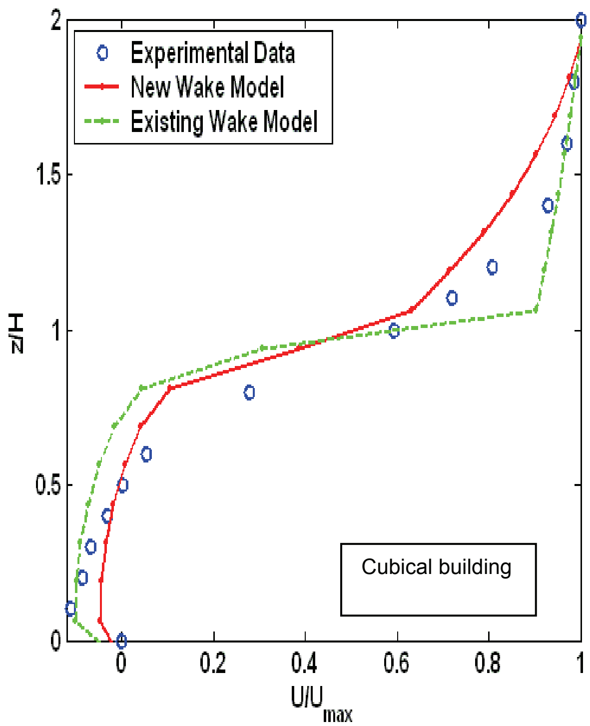

Figure 9. Comparison of model-computed and measured vertical profiles of velocity on the centerline at X/H=1.0 for the new and original wake schemes.

Figure 10 shows a comparison of the model output with the wind-tunnel measurements in the vertical direction at X/H=1.5 downstream of the building. The new wake model gives a better estimate of the velocity profile from the ground to slightly above building height, but then underestimates the velocity. The original wake model shows the same disjointed velocity profile just above rooftop.

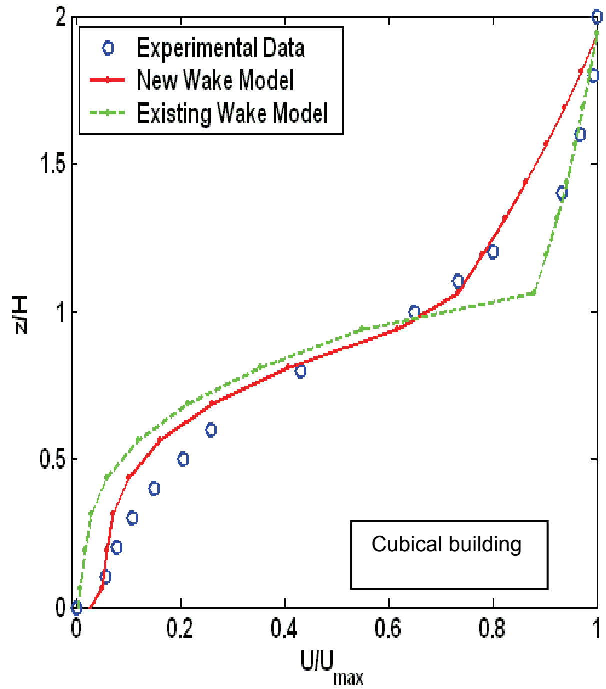

Figure 10. Comparison of model-computed and measured vertical profiles of velocity on the centerline at X/H=1.5 for the new and original wake schemes.

5.2 Wide Building

For the wide building, we compare the mean velocity profile in the lateral and vertical directions at X/H = 1.5. For the lateral profile the new wake model gives a better estimate of velocity outside Röckle's wake region as compared to the original wake scheme (Fig. 11). However, the new scheme under predicts the magnitude of the reverse flow velocity in the cavity region, while the original scheme provides better values.

Figure 12 shows the comparison of mean velocity at X/H = 1.5 in the vertical direction. The new wake model better captures the overall shape of the measured velocity profile as compared to the original scheme. The new scheme slightly overestimates the magnitude of the mean velocity just above building rooftop and slightly underestimates the magnitude of reverse flow near ground level.

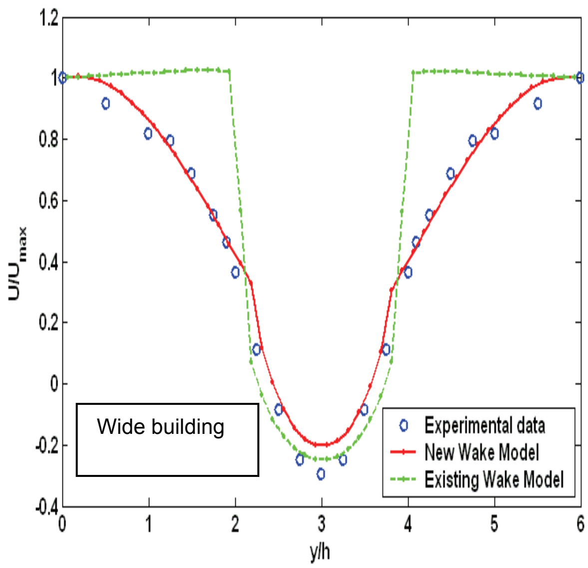

Figure 11. Comparison of model-computed and measured lateral profiles of velocity at X/H=1.5 and Z/H=0.1 for the new and original wake schemes.

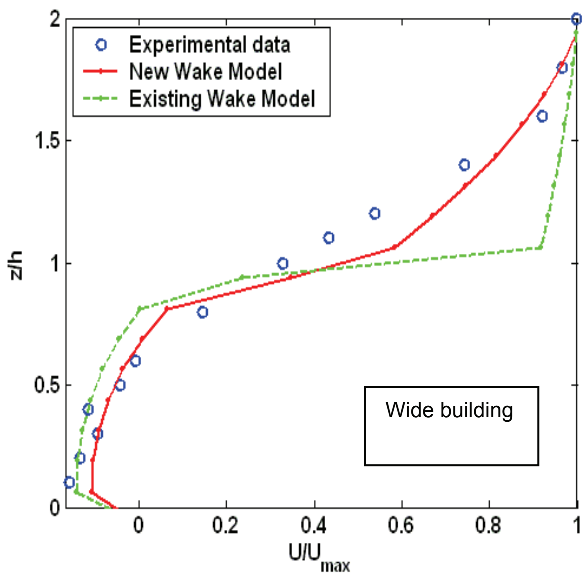

Figure 12. Comparison of model-computed and measured vertical profiles of velocity on the centerline at X/H=1.5 for the new and original wake schemes.

5.3 Tall Building

The mean longitudinal velocity profile at X/H=0.75 downstream of the back edge of the tall building was compared in both the crosswind and vertical directions. Figure 13 clearly shows that the new wake model better estimates the overall profile shape. Velocities directly behind the building are also better estimated.

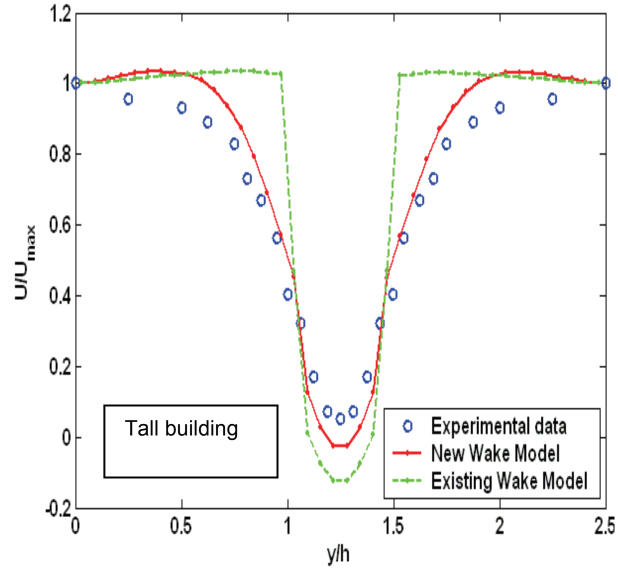

Figure 13. Comparison of model-computed and measured lateral profiles of velocity at X/H=0.75 and Z/H=0.1 for the new and original wake schemes.

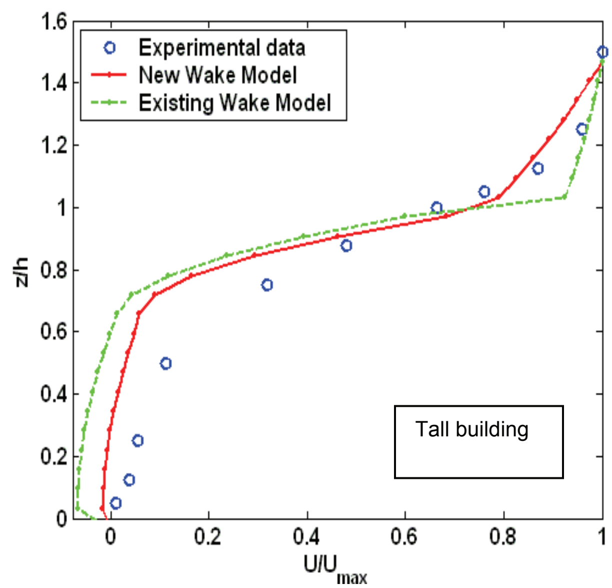

Figure 14. Comparison of model-computed and measured vertical profiles of velocity on the centerline at X/H=0.75 for the new and original wake schemes.

Figure 14 shows the mean longitudinal velocity profile in the vertical direction at X/H=0.75. The new wake model has a smoother profile, in better agreement with the measurements. However, both the new and original schemes underestimate the velocity below building height.

6. Summary & Future Work

The purpose of this work was to evaluate the QUIC-URB wake parameterization schemes. The wake velocities estimated by QUIC-URB were compared with experimental data for a cubical, wide, and tall building. The original scheme revealed velocity gradients around the edge of the cavity and wake region that was much too strong. A new wake model was proposed that would better represent the smooth transition of velocity from inside to outside the original cavity and wake regions.

Comparisons of lateral and vertical velocity profiles showed that the new scheme better matches experimental results in the wake region.

Preliminary tests are now being conducted for a group of buildings to ensure the model performance when wakes overlap and interact. Figure 15 shows an x-z plane of vectors colored by wind speed for the original wake model (top) and the new wake model (bottom). In the former, there is almost no diffusion of momentum in the vertical direction. Sharp velocity gradients are present near the top of the building rooftops. The new wake model shows slower velocities above rooftop downwind of each building, agreeing with expectations. Future work will include evaluating the new wake scheme against multi-building experimental datasets.

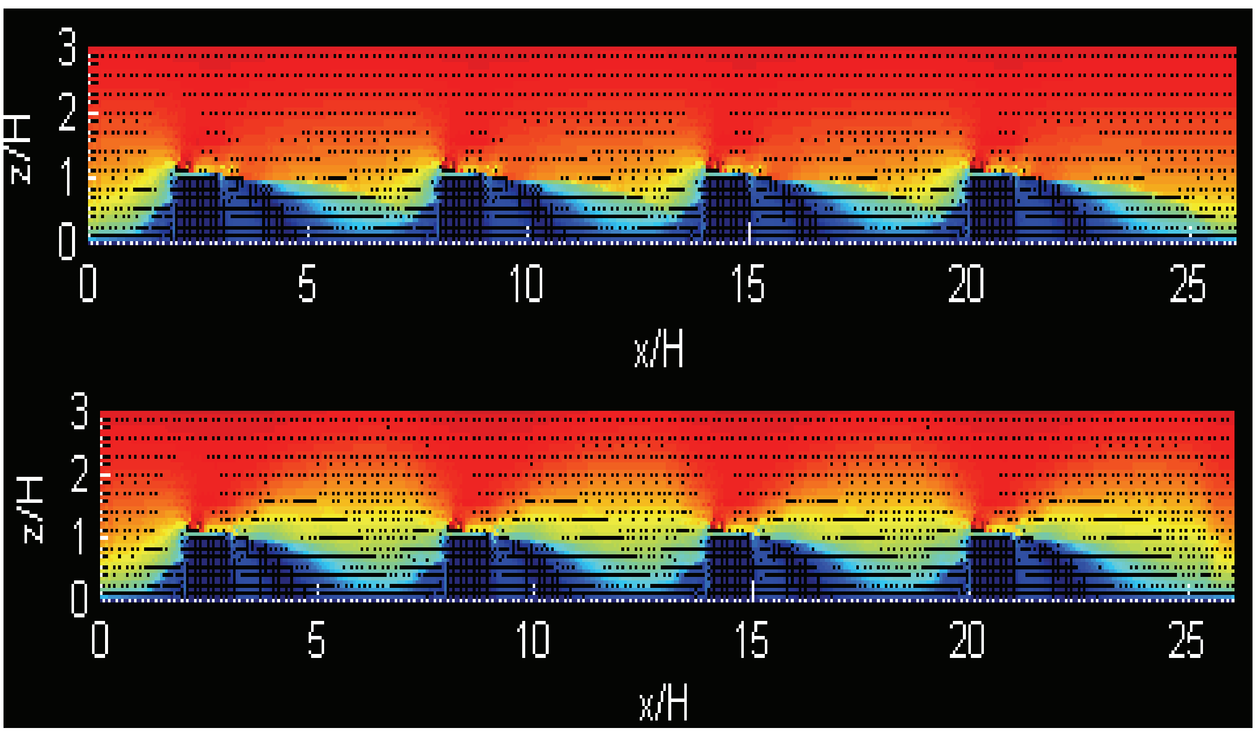

Figure 15. Comparison of wind vectors colored by wind speed along the centerline of an array of buildings for the original wake scheme (top) and the new wake scheme (bottom). Flow from left to right.

References

Kaplan, H. and N. Dinar, (1996), "A Lagrangian Dispersion Model for Calculating Concentration Distribution within a built-up domain" *Atmospheric Environment, 30, 4197-4207.*

Kastner-Klein, P., E.R. Pardyjak, and M. Brown, (2003), "Evaluation of the fast response model QUIC-URB based on wind-tunnel flow measurements in idealized street canyon" *Abstract for the 11th Conf. on Wind Engineering, June 2-5 2003, Lubbock, TX.*

Pardyjak, E.R. and M.J. Brown, (2001), "Evaluation of a Fast-Response Urban Wind Model-Comparison to Single-Building Wind Tunnel Data" *Los Alamos National Laboratory report LA-UR-01-4028.*

Pardyjak, E. and M. Brown, (2002), "Fast response modeling of a two building urban street canyon" *4th AMS Symp. Urban Env., Norfolk, VA, May 20-24 2002, LA-UR-02-1217.*

Pardyjak, E. and M. Brown, (2003), "QUIC-URB v1.1: Theory and User's Guide", *Los Alamos National Laboratory.*

Röckle, R. (1990), "Bestimmung der Stomungsverhaltnisse im Bereich komplexer Bebauungsstrukturen" *Ph.D. thesis, Vom Fachbereich Mechanik, der Technischen Hochschule Darmstadt, Germany.*

Röckle, R., C.-J. Richter, Th. Salomon, F. Dröscher, and J. Kost, (1998), "Ausbreitung von Emissionen in komplexer Bebauung - Vergleich zwischen numerischen Modellen und Windkanalmessungen" *Projekt eropäisches Forschungszentrum für Maßnahmen der Luftreinhaltung, PEF 295002.*

Snyder, W.H., and R.E. Lawson, (1994), "Wind-tunnel measurements of flow fields in the vicinity of buildings" *8th Joint Conf. on Applic. of Air Poll. Meteor. with AWMA, Nashville, TN, Amer. Meteor. Soc., 23-28.*

Taylor, P.A. and J.R. Salmon, (1993), "A model for the correction of surface wind data for sheltering by upwind obstacles" *J. Appl. Meteor., 49, 226-239.*