JP6.4 Evaluation of an Urban Vegetative Canopy Scheme and Impact on Plume Dispersion

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1. INTRODUCTION

The Quick Urban and Industrial Complex (QUIC) atmospheric dispersion modeling system attempts to fill an important gap between the fast, but non-building-aware Gaussian plume models and the building-aware but slow computational fluid dynamics (CFD) models. While Gaussian models have the ability to give answers quickly to emergency responders, they are unlikely to be able to adequately account for the effects of the building-induced complex flow patterns on the near-source dispersion of contaminants. QUIC uses a diagnostic mass-consistent empirical wind model called QUIC-URB that is based on the methodology of Röckle (1990), (see also Kaplan and Dinar 1996). In this approach, the recirculation zones that form around and between buildings are inserted into the flow using empirical parameterizations and then the wind field is forced to be mass consistent. Although not as accurate as CFD codes, this approach is several orders of magnitude faster and accounts for the bulk effects of buildings.

Since vegetation is common in urban areas and can significantly affect the flow around them, accurate simulation of building resolved urban flow requires the inclusion of vegetative effects. Due to the fact that QUIC-URB does not use all of the physics that CFD models do, vegetative effects are added using empirical parameterizations. The original vegetation canopy algorithm in QUIC-URB was only used to modify the initial flow field. As per MacDonald (2000), the Cionco (1965) canopy profile was applied to the flow within the canopy and the flow above the canopy was given a logarithmic profile regardless of the type of velocity profile used to initialize the wind field. The vegetative canopies that overlap with the building parameterization regions would be overwritten by the building flow. Originally the turbulence algorithms in QUIC's dispersion code QUIC-PLUME computed the turbulence parameters in the same way that it did for flow in open areas using Prandtl mixing length methods. In this work we discuss modifications to the vegetative flow algorithms in QUIC-URB, which include vegetative effects on building flow regions, non-logarithmic inflow profiles, and turbulence. Evaluation of these modified algorithms against wind-tunnel and field data will also be presented.

2. MODIFICATIONS TO THE VEGETATIVE FLOW ALGORITHM

2.1 *Mean Velocity Components*

2.1a *Vegetation in Open Areas*

As was stated in the introduction the original vegetative flow algorithm in QUIC-URB was based on the work of MacDonald (2000). This parameterization assumes a logarithmic upwind profile (Eq. 1).

$$U(z)=\frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)=\frac{U_{ref}\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{1}$$

Where z is the height above the ground, z_0 is the aerodynamic roughness length of the surface, u_* is the friction velocity at the surface, and κ is the von Karman constant, which is assumed to have a value of 0.4. On the right is the form of the logarithmic profile that is often used in QUIC-URB since it easily lends itself to the use of a single meteorological measurement point with a velocity (U_{ref}) measured at a height (z_{ref}). The value for z_0 is typically assumed using local surface characteristics. The logarithmic inflow profile is modified below the canopy height (H) using Cionco's exponential profile (Eq. 2).

$$U(z)=U_H\exp\left(\alpha(z)\left(\frac{z}{H}-1\right)\right) \tag{2}$$

Where U_H is the velocity at the top of the canopy and α is the attenuation coefficient of the canopy. The original algorithm kept α constant with height. Cionco (1978) provides a fairly extensive list of α values for a wide variety of vegetation canopies.

High above the canopy the wind profile is assumed to have a logarithmic profile modified by a displacement length (d) as is seen in Eq. 3.

$$U(z)=\frac{u_*}{\kappa}\ln\left(\frac{z-d}{z_0}\right) \tag{3}$$

MacDonald also included a transition region through the roughness sublayer (RSL), which was intended to remove any potential discontinuities in the velocity gradients. However in practice the transition region parameterization is somewhat cumbersome as it includes several parameters that are difficult to determine a priori. Optimization of these parameters would typically involve a lot of trial and error.

In order to simplify the number and availability of the parameters involved in the vegetative flow scheme, the QUIC implementation of MacDonald's

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parameterization was restricted to the canopy and modified logarithmic profile. U_{ref} in the flow above the canopy is taken as the velocity at H to ensure that there is no discontinuity in the velocity at H. While it leaves the possibility of discontinuities in the velocity gradient at the top of the canopy, it is composed of parameters that are relatively easy to obtain or estimate.

While this parameterization is straightforward it has several shortcomings. First and foremost is that the vegetation effects on the initial wind field are overwritten by the building parameterizations. Another limitation lies in requiring α being constant with height. Most urban vegetation, particularly in the dense urban centers, consists of trees instead of uniform canopies such as fields of grain. In addition the wind direction at the top of the canopy was propagated throughout the profile, which is an issue when applying the vegetative algorithm to a wind field with directional shear in the profile. The algorithm also imposes a logarithmic profile above the canopy regardless of the profile shape used to initialize the wind field.

Since the standard canopy profile is essentially a modification to an undisturbed upwind profile it is unclear what the profile should be in the building flow regions or how a profile with directional shear should be affected by a vegetation canopy. As a first cut at this issue, we try to look at the canopy as a simple fractional reduction of the initial velocity. In order to determine the dependence of the velocity reduction fraction we compare the profile within the canopy with the undisturbed profile (assuming it to be logarithmic).

Since the canopy profile is divided into two regions (above the canopy height and below it) the reduction factor must also be divided into two regions. For simplicity we assume that z_{ref} is equal to the H and therefore U_{ref} is the upwind velocity at H.

$$U_0(z) = \frac{U_{ref} \ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)} \tag{4}$$

For simplicity, we also assume that u_* and z_0 remain constant between the upwind profile and the canopy profile even though one would normally expect the canopy to increase both of these values. In order to account for stacked vegetation canopies the value of H is the highest canopy height for a given position (x,y) and the properties of the wind profile above the canopy are calculated as if the canopy at (x,y) was continuous from ground level up to H and had a constant α with value equal to $\alpha(H)$. However, the actual canopy does not need to have a constant α or even be continuous. The profile above the canopy is assumed to still be logarithmic but modified by d. Thus the assumed velocity profile above the canopy is:

$$z > H, \qquad U(z) = \frac{U_{ref} \ln\left(\frac{z-d}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)} \tag{5}$$

The velocity at the top of the canopy is calculated from the modified logarithmic profile above the canopy to avoid discontinuities in the velocity at the transition between the two regions. Thus the assumed velocity profile within the canopy is:

$$z \le H,$$

$$U(z) = \frac{U_{ref} \ln\left(\frac{z-d}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)} \exp\left(\alpha(z)\left(\frac{z}{H}-1\right)\right) \tag{6}$$

The reduction factor (F) is defined as the ratio of the velocity modified by the canopy at a given z to the undisturbed velocity at the same height.

$$F(z) = \frac{U(z)}{U_0(z)} \tag{7}$$

Above the canopy this reduces to:

$$z > H, \qquad F(z) = \frac{\ln\left(\frac{z-d}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)} \tag{8}$$

Within the canopy this reduces to:

$$z \le H, F(z) = \frac{\ln\left(\frac{H-d}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)} \exp\left(\alpha(z)\left(\frac{z}{H}-1\right)\right) \tag{9}$$

Now that we have determined the reduction factor profile the effects of the canopy at (x,y) are produced in the canopy by simply multiplying the initial velocities at (x,y,z) by $F(z)$. To avoid sharp kinks in the velocity profile α is averaged at the interfaces within the canopy. $F(z)$ is also restricted to being between 0 and 1, ensuring the a canopy cannot accelerate or reverse the flow within it, which could otherwise occur given the right combination of parameters.

2.1b *Vegetation in Building Flow Regions*

Since it is unclear what effect the vegetation will have on the building flow above it we will restrict vegetation effects in building flow regions to below H. Note that for simplicity we have also assumed that velocity at the top of the canopy profile (U_H) is the same as the building flow velocity value at H, which is not true since canopy profile uses a velocity measurement at the top of well-developed canopy flow. Typically the velocity of the flow at the top of the canopy should be reduced from the undisturbed flow, but since canopies that are found within building flow regions are likely to be relatively small it is unlikely that they would produce well-developed canopy flow. Again because we do not know a priori what the actual velocity profile within the building flow region will be we assume it to be logarithmic:

$$U_0(z) = \frac{U_H \ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)} \tag{10}$$

We also assume that the velocities within the canopy still have the Cionco exponential form in Eq. 2. Using these assumptions the reduction factor reduces to:

$$F(z) = \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)} \exp\left(\alpha(z)\left(\frac{z}{H} - 1\right)\right) \tag{11}$$

Similar to the procedure for open regions, the velocities within a canopy that is found in a building flow region can then be modified by simply multiplying the velocities (after the building parameterizations have been applied) within the canopy by the reduction factor corresponding to the height within the canopy.

2.2 *Turbulence*

Turbulence in QUIC-PLUME is generated from the mean wind field produced by QUIC-URB using Prandtl mixing length methods. A local coordinate system is used that is rotated such that one of the principal axes will be in the direction of the largest velocity gradient while another principal axis will be aligned with the mean wind vector. This velocity gradient is then used with a mixing length (*L*) to estimate a local u_* from which the other rms velocity components are estimated.

In previous versions of the QUIC-PLUME model, there was no adjustment for the presence of a vegetation canopy. Consequently, very high turbulent kinetic energies were simulated for the atmosphere slightly above the canopy top where there were large velocity gradients. We have developed adjustments for turbulence in the presence of vegetative canopies by changing the turbulence length scale in the vegetation and above the top of the canopy. Within the canopy we increase the length scale with height until it reaches the estimated length scale for the canopy (L_c), as a whole. Consequently,

$$L = L_c \frac{z - z_0}{0.3H} \tag{12}$$

when $z > \frac{z - z_0}{0.3H}$, we use:

$$L = L_c \tag{13}$$

where L_c is calculated using the formula found in MacDonald (2000).

$$L_c = \frac{H u_*}{\alpha(H) U_H} \tag{14}$$

Note that this formula for L_c assumes α to be constant with height and a well-developed canopy. Thus the change in α with height is only accounted for in the turbulence by the effects varying α has on the velocity gradients. Above the canopy, we use:

$$L = \kappa(z - H) + L_c \tag{15}$$

At the top of the canopy where the velocity gradients are strongest a shear layer mixing length is used (Eq. 16).

$$L = \frac{\kappa U}{dU/dz} \tag{16}$$

3. MODEL EVALUATION

In order to validate the latest QUIC scheme for flows through and above vegetative canopies we compared simulation results with experimental results previously reported in literature.

The wind tunnel data used for validation were published by Finnigan and Mulhearn (1978), hereafter referred to as F&M. The wind tunnel dimensions were 12 m length, and cross section was 1.83 m x 0.61 m. The canopy was intended to simulate wheat. The model wheat stalks were made of nylon fishing line. The canopy was 52 cm long, 40 cm wide and 5 cm deep. The upwind profile was measured with the model removed from the wind tunnel. A logarithmic curve fit to the wind-tunnel data yields a z_0 of $1.017e^{-5}$ m. It should also be noted that the boundary layer in the wind tunnel was artificially roughened using relatively large gravel with an average diameter of 14 mm extending 4.28 m immediately upwind of the modeled canopy. Given the extremely small roughness length of the upwind profile, this roughness was not included when measuring the upwind profile. A curve fit to the profile downwind of the canopy yielded a z_0 of about 24 mm. Unfortunately the contribution of the canopy cannot be separated from this value so the small value obtained from the empty wind tunnel was used in the simulation. A curve fit to the wind tunnel data within the canopy yielded a α of 1.247 which was then used in the QUIC simulation. The QUIC domain size was 1 m long, 1 m wide and 0.6 m high.

Both wind tunnel and simulated upwind mean velocity profiles are shown in Fig. 1. The upwind root-mean squared (rms) streamwise and vertical velocity components are shown in Fig. 2. It can be seen in these figures that while the upstream profile in the wind tunnel is not logarithmic; the logarithmic velocity profile does a reasonable simulation of the streamwise mean and rms velocities. The turbulence scheme in QUIC uses the Prandtl mixing length to determine u* and then assumes standard atmospheric surface layer relationships between u* and the rms velocity components. Thus using a logarithmic profile will produce constant rms velocities with height as is seen in Fig. 2.

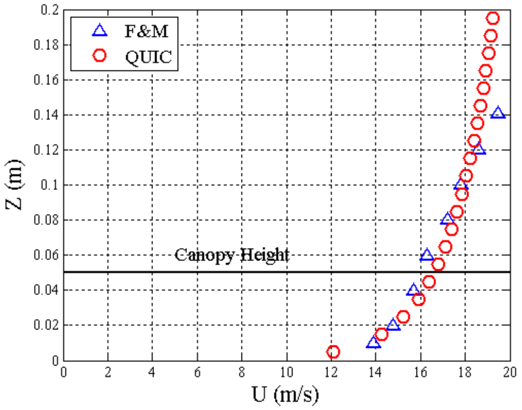

Figure 1. Comparison of the mean upwind velocities in the wind tunnel and the modeled mean upwind velocities from QUIC.

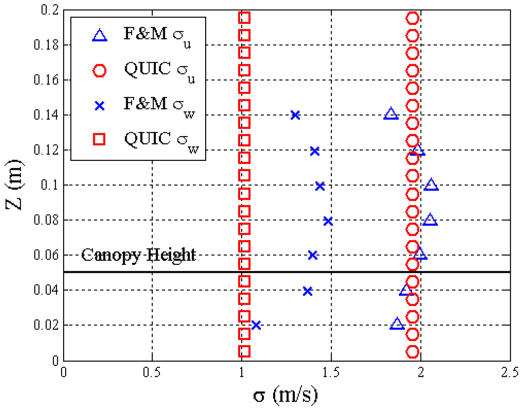

Figure 2. Upwind streamwise and vertical rms velocity components for the wind-tunnel data and the QUIC simulation.

The mean velocity and the friction velocity within the canopy are shown in Figs. 3 and 4, respectively. The mean velocities in Fig. 3 show that the simulated velocities within the canopy slightly overestimate the velocities within the model canopy. This is likely due to a combination of two effects. First the initial wind field in the simulation used the unroughened upwind profile found in the literature, which leads to a higher velocity at the top of the canopy. Second, the assumption that u* and z_0 are not modified by the presence of the canopy, which will also contribute to a higher velocity at the top of the canopy. While there are some discrepancies in the velocities at the top of the canopy QUIC produces turbulence that is remarkably similar to the values seen in the wind tunnel data in Fig. 4. Previous versions of QUIC used the same mixing length within a canopy as would be produced out in the open at the same height. This resulted in enormous turbulence within and just above a canopy since identical mixing lengths were paired with much stronger velocity gradients with and above the canopy. This produced peak turbulence values that were two orders of magnitude too high.

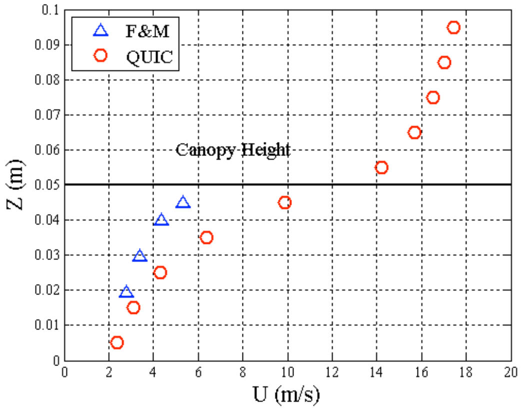

Figure 3. Mean velocities within the canopy.

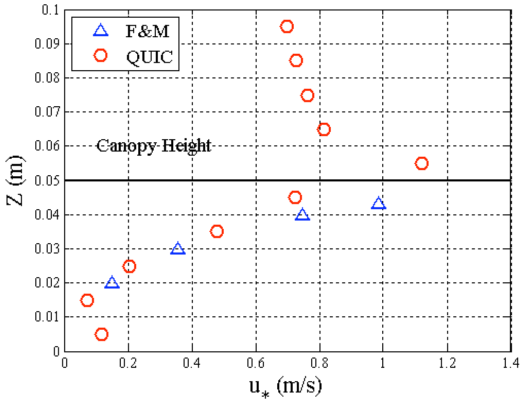

Figure 4. Friction velocity within the canopy.

4. CONCLUSIONS

The modifications to the vegetation canopy parameterizations in QUIC have made them more flexible and have significantly improved the resulting turbulence fields. The new algorithms have the ability to: apply vegetation effects in building flow regions as well as open areas; have a variable attenuation coefficient, which make simulations of tree canopies more realistic; and more realistically affect wind fields with directional shear.

As a demonstration of the ability to incorporate attenuation coefficients that vary with height is shown in Fig. 5. This is a comparison of a canopy that has $\alpha = 1.247$ throughout the canopy with another that has $\alpha = 0.5$ up to 3 cm and $\alpha = 1.247$ between 3 and 5 cm.

The overall effect of vegetation on dispersion is shown in Figs. 6 and 7. Two identical sources were released simultaneously. The lower source was released in upwind of a canopy while the upper source was allowed to disperse without a canopy. Fig. 6 shows snapshots of the plume at a) time = 0, b) time = 30 s, and c) time = 60 s. Part of the plume gets trapped within the canopy significantly slowing the passage of the plume. After 60 s the plume in the open has almost completely left the domain while a large portion of the other plume remains in the canopy. The difference in the duration of the passage of the plume also affects the resulting dosage fields as is shown in the near surface dosages in Fig. 7. The slower velocities within the canopy trap the portion of the plume that enters the canopy increasing the exposure time and therefore increasing the resulting dosage within the canopy.

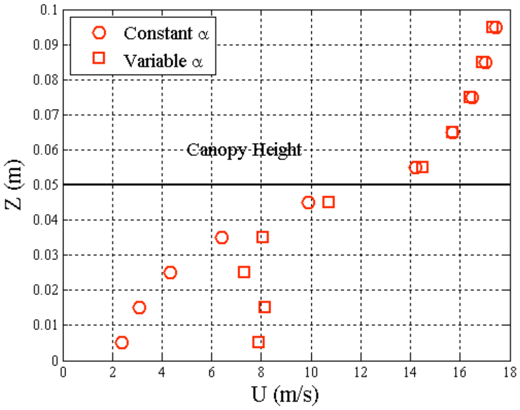

Figure 5. Comparison of a canopy with α being constant with height and another where α varies with height.

While the current modifications to the canopy algorithm in QUIC are a significant improvement on the previous algorithm, further modifications remain to make the treatment of vegetation canopies in QUIC even more realistic. As was mentioned previously the u_* and z_0 are assumed to be unaffected by the presence of the canopy when in reality one would expect them both to be enhanced by the vegetation roughness. The current algorithm also assumes fully developed canopy flow where a canopy with a finite extent will produce an internal boundary layer that will develop with downwind distance over the canopy. Finally canopies produce wakes that affect the flow downwind of them. In the current version of QUIC the flow downwind of a canopy is only affected by the presence of the canopy through enforcing mass conservation on the flow which does some smoothing of the transition between the flow within the canopy and the flow downwind of the canopy.

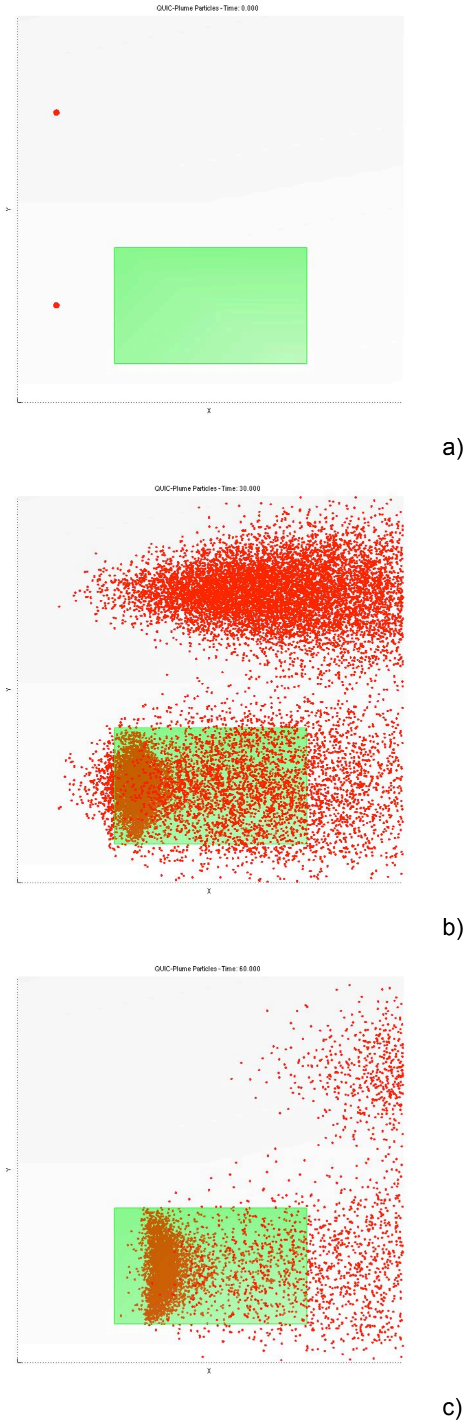

Figure 6. Plan view comparison of a plume moving through the open (above) and through a canopy (below) at t = 0 s (a), t = 30 s (b), and t = 60 s (c). The location of the vegetative canopy is depicted using the transparent green box.

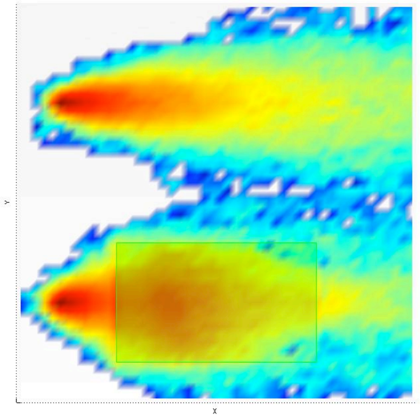

Figure 7. Plan view comparing the dosage fields of one plume dispersing through the open (above) and another through a canopy (below). The location of the vegetative canopy is depicted using the transparent green box.

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