The Shear Layer above and in Urban Canopies

PABLO HUQ,* ALEJANDRO CARRILLO,*,+ LOUIS A. WHITE,* JOSE REDONDO,+ SESHU DHARMAVARAM,# AND STEVEN R. HANNA@

*College of Marine and Earth Studies, University of Delaware, Newark, Delaware
+ Universitat Politecnica de Catalunya, Barcelona, Spain
# DuPont Company, Wilmington, Delaware
@ Hanna Consultants, Kennebunkport, Maine

(Manuscript received 21 December 2005, in final form 31 July 2006)

ABSTRACT

The nature and role of the shear layer, which occurs at the level of the average building height in urban canopies, are poorly understood. Velocity data are analyzed to determine the characteristics of the shear layer of the urban canopy, defined as the broad, linear segment of the mean velocity profile in a region of high shear. Particle image velocimetry measurements in a water tunnel were undertaken to resolve velocity profiles for urban canopies of two geometries typical of Los Angeles, California, and New York City, New York, for which the aspect ratios (average building height-to-width ratio) H/w_b are 1 and 3, respectively. The shear layers evolve with distance differently: For $H/w_b = 1$ the urban canopy shear layer extends quickly from above the building height to ground level, whereas for $H/w_b = 3$ the urban canopy shear layer remains elevated at the vicinity of the building height, only reaching to a depth of $z/H \sim 0.5$ far downstream. Profiles of the mean velocity gradient also differ from each other for urban canopies associated with H/w_b of 1 or 3. Values of shear dU/dz increase toward ground level for an urban canopy associated with $H/w_b = 1$. For an urban canopy associated with $H/w_b = 3$, localized peaks of shear dU/dz exist at the building height and at ground level, with values of shear decreasing to zero at building midheight and far above the building height. A consequence of the different forms of the shear layers of the two urban canopies is that the ground-level dispersion coefficient is likely to be greater for urban canopies associated with $H/w_b = 1$ than for those associated with $H/w_b = 3$ because of an increased ventilation and exchange mechanism for cities such as Los Angeles relative to cities such as New York City that possess urban canyons.

1. Introduction

Field data of the velocity profile within and above cities are scarce (and also expensive to obtain). Nonetheless, such information is a prerequisite toward developing an understanding of the dynamics of flow in and above cities (Roth 2000). The flow field over cities has similarities to (boundary layer) flow over rough surfaces, and much has been learned from comparison with the flow field of turbulent flow in plant canopies (Shaw et al. 1974; Finnigan 2000). Indeed, the term urban canopy is now commonly used when describing the airflow over cities or urban areas. Parameterizations for urban canopies have been developed for flow variables associated with boundary layer flow, such as friction velocity, shear stress, effective roughness length, displacement heights for momentum and shear stress, and extents of the roughness sublayer and inertial sublayer composing the boundary layer of the urban canopy (Jackson 1981; Oke 1987; Kaimal and Finnigan 1994; Rotach 1995; MacDonald et al. 1998; Brown et al. 2000; Britter and Hanna 2003; Kastner-Klein and Rotach 2004). Extensive field data have been collected in Oklahoma City, Oklahoma (Brown et al. 2004); London, United Kingdom [the Dispersion of Air Pollution and Penetration into the Local Environment (DAPPLE) program; Dobre et al. 2005]; and Basel, Switzerland (Rotach et al. 2005) to develop datasets of flows in cities. Observations show that the flow fields in all of the above urban canyons are locally inhomogeneous—for example, strong vortices exist at the corners of buildings—so that the generality of parameterizations may be limited.

Corresponding author address: Pablo Huq, College of Marine and Earth Studies, University of Delaware, Robinson Hall, Newark, DE 19716.
E-mail: huq@udel.edu

DOI: 10.1175/JAM2469.1

It has been established that flows in and above urban areas have similar mean velocity profiles to flows through plant canopies. Kaimal and Finnigan (1994) present data from field and wind-tunnel measurements, with the mean velocity profile normalized by the mean velocity at the height of the plant canopy. They found that introducing this method of scaling collapses the datasets. We find that a similar scaling is useful for urban canopies: the average building height H and the mean velocity U at the building height (at $z = H$), denoted as U_b. A nondimensional group that usefully distinguishes between canopies of similar areal arrangement but differing building heights is the aspect ratio H/w_b, where w_b is the average building width. Thus, urban canopies with $H/w_b = 1$ and with $H/w_b = 3$ are characteristic of midtown Los Angeles (LA), California, and New York City (NYC), New York, respectively. The mean velocity profiles of shear layers approximate a hyperbolic tangent (Ho and Huerre 1984); this attribute has proved to be useful in the analysis of flow within and above plant canopies (Raupach et al. 1996) as well as in aquatic flows with submerged vegetation (Ghisalberti and Nepf 2002). We find that it is also helpful in the analysis of flow above and in urban canopies.

Laboratory experiments have been useful in urban boundary layer research. Studies in water tunnels have established the characteristics of probability distributions of scalar fluctuations in turbulent boundary layer flows (Yee et al. 1993). Brown et al. (2000) and Schatzmann and Leitl (2002) found high turbulence levels occurred above buildings and that vortices formed behind buildings in wind-tunnel tests of urban canopies. Jimenez (2004) provided a summary of experimental data on turbulent flows over rough walls and discriminated the role of the roughness Reynolds number and the ratio of the boundary layer thickness to the roughness height in determining whether a logarithmic profile exists. Kastner-Klein and Rotach (2004) discussed the mean flow and turbulence characteristics in a wind-tunnel urban boundary layer that utilized high-resolution measurements "inside and above a realistic urban canopy with highly variable building heights and shapes." A useful method to calculate the roughness height z_0 and displacement height d of a model urban canopy comprising an array of obstacles in a wind tunnel was developed by MacDonald et al. (1998). He utilized a frontal area density λ_f and a plan area density λ_p to characterize urban canopies and evaluated drag forces to determine how z_0 and d varied with area density; the use of λ_f and λ_p to characterize urban canopies is now standard (where $\lambda_f = A_f/A_T$ is the ratio of the building frontal area A_f to the building lot area A_T and $\lambda_p = A_p/A_T$ is the ratio of the building plan area A_p to the building lot area A_T). Note that λ_p does not distinguish between urban canopies of differing average building heights and that λ_f does not distinguish between urban canopies with differing arrangements of similar buildings. It is evident that it is difficult to characterize urban canopies with a single parameter. Thus, in general, we adopt the practice of using the parameter H/w_b as well as λ_f and λ_p to characterize urban canopies.

The principal feature of the flow over an urban canopy is a turbulent shear layer that occurs in the vicinity of the mean building height. This shear layer separates the broadly uniform but faster-moving turbulent layer above from the broadly uniform but slower-moving turbulent layer below (see Figs. 1 and 3, both of which are described in more detail below). To date there has been little research on the character and dynamics of this shear layer. The purpose of this paper is to address this shortcoming. High-resolution measurements, both temporal and spatial, are undertaken in model urban canopies in a water tunnel. Measurements are taken of the velocity and scalar field for both mean and turbulent quantities; in this paper, we only report on mean velocities. Other measurements are reported elsewhere (Huq et al. 2007, manuscript submitted to *Bound.-Layer Meteor.*). Laboratory data are undertaken for two urban canopies with aspect ratios H/w_b = 1 (hereinafter denoted as Hwb1) and $H/w_b = 3$ (hereinafter denoted as Hwb3), respectively. An Hwb1 urban canopy is representative of midtown LA; an Hwb3 urban canyon is representative of midtown NYC. The comparison between the different canopies facilitates understanding of the flow in deep urban canyons typical of NYC, London, and Tokyo, Japan.

The objectives of the experiments are to quantify important structural features of the shear layer for canopies of different aspect ratios. Such quantification is important for understanding the mechanics of dispersion in urban canopies and the vertical turbulent exchange processes between the urban canopy and the overlying atmosphere. We also present normalized data of the velocity field in urban canopies in forms useful for numerical modeling.

2. Experimental method

Laboratory experiments were undertaken at the Environmental Fluids Laboratory at the University of Delaware. The water tunnel is 400 cm long, 40 cm deep, and 25 cm wide and is constructed from Plexiglas. The Plexiglas walls allow the use of flow visualization techniques in addition to particle image velocimetry (PIV) and conductivity probe measurements. The water tun-

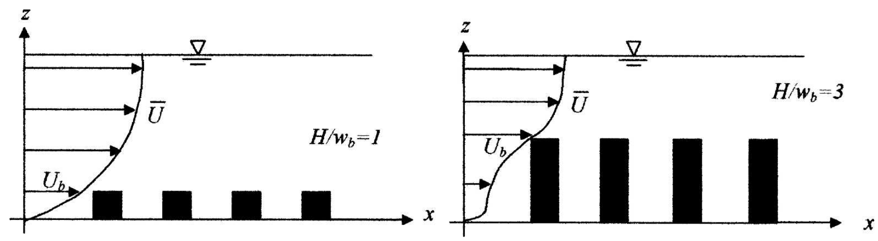

FIG. 1. Schematic of the experimental flow configuration for urban canopies with aspect ratios H/w_b of (left) 1 and (right) 3. Note that the mean velocity profile resembles a boundary layer profile for an Hwb1 urban canopy; in contrast, the mean velocity profile for an Hwb3 urban canopy approximates a shear-layer profile that is "tanh" like.

nel is designed to operate with stratification; however, for this experiment only neutral conditions are investigated. The total water depth in the tunnel is approximately 30 cm, and free-stream velocities were approximately 10 cm s^{-1}. For all experiments, the flow was in steady state. A Counihan vortex generator of 10-cm height, located upstream of the working section, is used to promote boundary layer development (Counihan 1969). Values of Reynolds number were approximately 10 000, which is sufficient for fully turbulent flow (Meroney 1990).

Two homogeneous urban canopies with aspect ratios H/w_b of 1 and 3 are used to compare cities that have shallow urban canyons (such as LA) with cities that have very deep urban canyons (such as NYC), respectively (see Fig. 1). Dimensions of the uniform height canopy are defined in Fig. 2. Here, H is the building height, B is the longitudinal (corresponding to along the x axis) building width, w_b is the lateral or transverse building width, G is the lateral or transverse spacing between buildings, and S is the longitudinal spacing between buildings. The canopies consist of 22 rows of three 3.2-cm-per-side square buildings, spaced 3.5 cm laterally and 5 cm longitudinally. The space between the buildings in a longitudinal direction is defined as the urban street canyon. The values for the areal densities λ_f and λ_p are both 0.186 for an urban canopy of aspect ratio $H/w_b = 1$; for an urban canopy with aspect ratio $H/w_b = 3$, values for λ_f and λ_p are 0.559 and 0.186, respectively. The values of $\lambda_f = 0.186$ and 0.559 are representative of the frontal densities λ_f in midtown LA and midtown NYC, respectively. Note that the ratio G/w_b in this study is approximately $O(1)$. The influence of this nondimensional parameter needs to be investigated, especially for the case in which $G/w_b < 1$.

The buildings are arranged in a regular array, as opposed to an irregular array, so that the urban canyons are particularly well defined. This arrangement, together with the uniform building height, represents an obvious idealization of a real city. It is prudent to remark on limitations arising from such idealization. Hall et al. (1996) examined the flow fields of both regular and staggered models of an urban canopy in a wind tunnel and found that the roughness lengths z_0 were greater for staggered arrays. The lack of variation of building height of the idealized urban canopy may not accurately represent the "skimming flow" regime (Oke 1987) that occurs at larger areal densities of $\lambda_f \geq 0.2$. The most likely consequence of our idealized regular and uniform height representation of an urban canopy is that the large localized values of the velocity gradient measured at rooftop levels in our study (see Fig. 10, described in detail below) are an overestimate. This is likely because localized values of $(dU/dz)w_b/U_b$ measured at rooftop levels in urban canopies with nonuniform heights will be smeared or diffused by the varying building heights.

Velocity measurements were taken along the centerline of the urban canyon in the x–z plane. A PIV system was used to obtain mean and fluctuating velocity quantities (U, u', and w'), including shear stress $\overline{uw}$, and

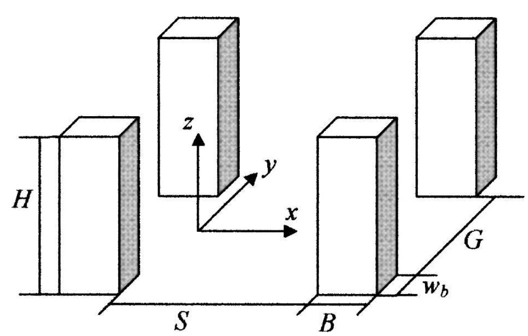

FIG. 2. Schematic showing parameters used to define urban canopy dimensions. Square blocks of length $B = 3.2$ cm, width $w_b = 3.2$ cm, and height $H = 3.2$ or 9.6 cm are arranged in a regular grid to form urban canopies with aspect ratios $H/w_b = 1$ and 3, respectively. Lateral spacing G between obstacles is 3.5 cm, and longitudinal spacing S is 5 cm, yielding a plan area density λ_p of 0.186 for both aspect ratios and frontal area densities λ_f of 0.186 and 0.559 for $H/w_b = 1$ and $H/w_b = 3$, respectively.

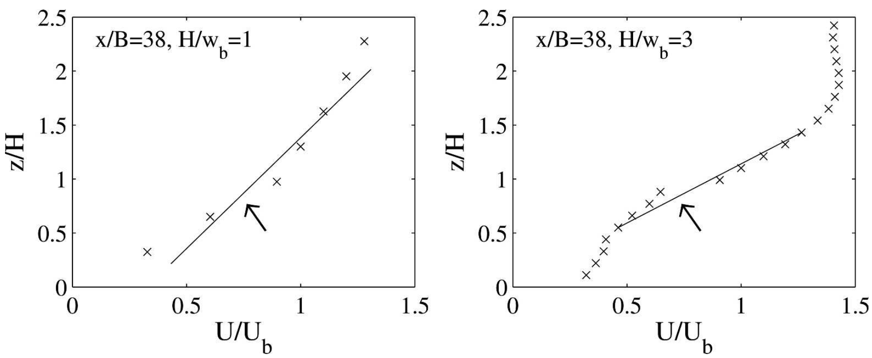

FIG. 3. Mean velocity profiles for Hwb1 and Hwb3 urban canopies at a downstream location x/B = 38. The vertical extent, or thickness, of the elevated shear layer in the vicinity of the building height is shown by the straight line.

each time series was typically 60 s in duration. (For the typical scales of the flow field, eddy turnover times were approximately 2 s; thus a 60-s time series contains about 30 eddies. This is sufficient for stable values of quantities arising from statistical analysis of the fluctuating velocities.) A video camera was used to record images of the passing particles at 30 Hz for various x locations (10, 32, 70, 90, and 122 cm). Experiments were performed at night to minimize disturbances from other lighting sources and to improve quality of the data. The estimates of error are 5% in mean velocity, 10% in rms velocity, and 15% for shear stress $\overline{uw}$. We have attempted to present laboratory data in a manner that will facilitate comparison with field data.

Flow in the tunnel resembles a boundary layer (i.e., power law) profile for an Hwb1 urban canopy, whereas for the Hwb3 urban canopy the velocity profile has an inflection point just below the building height. The value of the mean velocity at the building height (z/H = 1) is defined as U_b; this velocity scale U_b is used to nondimensionalize velocity profiles. Average values of U_b for H/w_b = 1 are 5.9 cm s^{-1}; for H/w_b = 3, values of U_b are 7.1 cm s^{-1} for distances up to x/B = 10 and 7.6 cm s^{-1} for larger distances. Figure 3 shows velocity profiles for Hwb1 and Hwb3 urban canopies and how we define the shear-layer thickness; endpoints of an empirical straight line fit through the extent of the linear region of the velocity profile are the vertical limits of the shear layer (e.g., for the Hwb3 urban canopy $U/U_b \sim 0.5$ at $z/H \sim 0.5$ and $U/U_b \sim 1.3$ at $z/H \sim 1.5$). The shear-layer thickness was calculated using this method for each x location.

3. Results and discussion

Nondimensional velocity profiles for the two urban canopies are presented in Figs. 4 and 5. (Here, height z and distance x are nondimensionalized by building height H and longitudinal building width B, respectively.) Broadly, the profiles for Hwb1 and Hwb3 urban canopies resemble a power-law boundary layer and a shear layer, respectively. (A well-known characteristic of shear layers is an inflection point in the middle of the profile; e.g., Kundu and Cohen 2004.) The profiles for Hwb1 urban canopy show that mean velocities below the building height or rooftop level $z/H \sim 1$ decrease with increasing values of distance x/B (e.g., for $z/H \sim 0.5$, $U/U_b \sim 0.8$ at $x/B \sim 3$ vs $U/U_b \sim 0.3$ at $x/B \sim 38$). Conversely, above the building height, mean velocities increase with distance x/B (e.g., for $z/H \sim 2$, $U/U_b \sim 1$

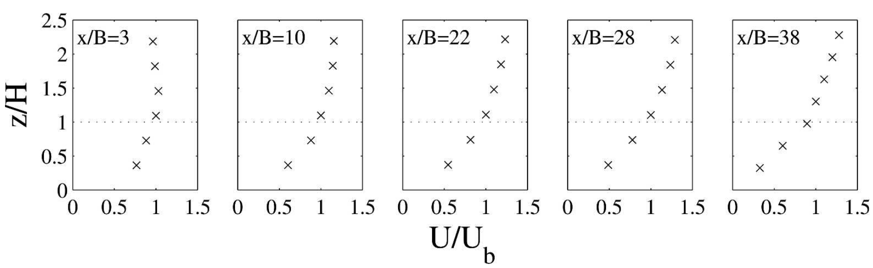

FIG. 4. Longitudinal evolution of the mean velocity profile for the Hwb1 urban canopy at various distances.

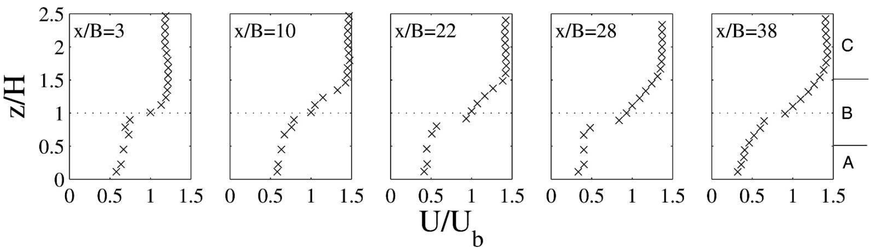

FIG. 5. Longitudinal evolution of the mean velocity profile for the Hwb3 urban canopy at various distances. Regions A and C indicate layers of turbulence with approximately uniform velocity below and above a turbulent shear layer B.

at $x/B \sim 3$ vs $U/U_b \sim 1.25$ at $x/B \sim 38$). For both Hwb1 and Hwb3 urban canopies the rate of change in the velocity profiles occur throughout the region from $x/B = 3$ to $x/B = 38$, rather than any particular fetch. Although the profile resembles a power-law boundary layer, the evolution of the mean velocity profile in the x direction (i.e., variation of the power-law index) is not representative of boundary layer behavior, and thus profiles cannot be fitted by a single boundary layer profile.

The velocity profiles for the Hwb3 urban canopy also evolve with distance x; it is evident in Fig. 5 that the shear-layer thickness increases with distance x. The profiles have three distinct vertical regions. Region A, ranging from ground level to building midheight ($0 < z/H < 0.5$), lies deep within the canopy and has small values of dU/dz ($\sim$0.3 s^{-1}); region B, ranging from building midheight to above the building height ($0.5 < z/H < 1.5$), has larger values of dU/dz ($\sim$1 s^{-1}) and possesses an inflection point—this layer is defined as the shear layer; region C above the canopy ($z/H > 1.5$) has small values of dU/dz ($\sim$0.3 s^{-1}). The Hwb3 urban canopy velocity profiles are similar in form to profiles observed in terrestrial and aquatic vegetated canopies (Kaimal and Finnigan 1994; Ghisalberti and Nepf 2002). Nondimensional mean velocity profiles were found to fit well to the hyperbolic tangent form determined by Ghisalberti and Nepf (2002) for canopies of aquatic flows with submerged vegetation. For the purpose of estimating mean velocities in urban areas, we propose a similar relationship using urban canopy parameters:

$$\frac{U - \overline{U}}{\Delta U} = 0.5 \tanh\left(\frac{z - H}{2\Delta z_{SL}/a}\right). \quad (1)$$

Here U is the mean velocity profile, $\overline{U}$ is the average of the velocities at regions A and C (see Fig. 5), ΔU is the difference in velocity between regions A and C, z is the vertical height above ground, H is the building height, Δz_{SL} is the shear-layer thickness, and the ratio $\Delta z_{SL}/a$ is the momentum thickness. (In physical terms, a is the ratio of the shear-layer thickness to the momentum thickness.) The value of a was determined empirically from the data to provide the best fit to the hyperbolic tangent profile. Figure 6 shows the measured mean velocity profiles for the Hwb3 urban canopy together with Eq. (1) for values $a = 5$ and $a = 7$ to check sensitivity.

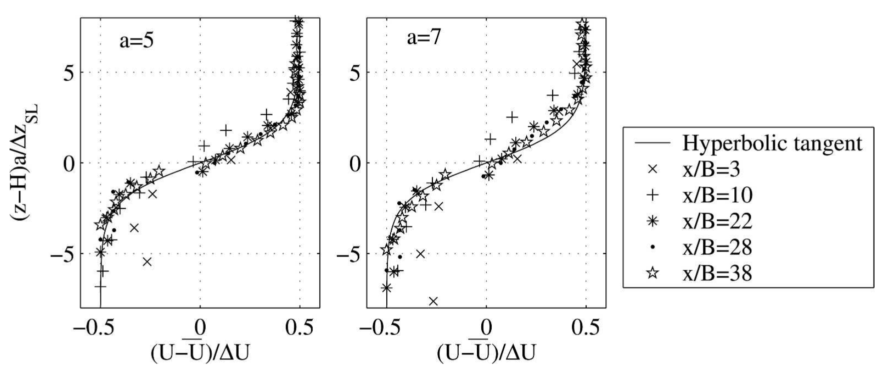

FIG. 6. Collapse of mean velocity data at various locations for the Hwb3 urban canopy to the hyperbolic tangent profile of Eq. (1). The panels use different values of a: (left) $a = 5$ and (right) $a = 7$. The collapse with $a = 5$ is best. The building height H is located at zero on the ordinate; zero on the abscissa corresponds to the mean velocity U_b at the building height.

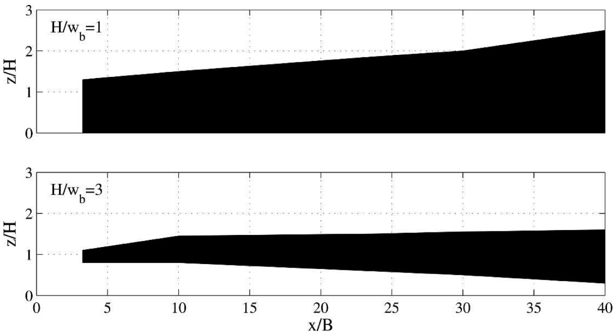

FIG. 7. Longitudinal evolution of the shear layer for Hwb1 and Hwb3 urban canopies. Note that the shear layer for the Hwb1 urban canopy reaches ground level. The shear layer of the Hwb3 urban canopy is elevated, and it grows at an overall rate of 7.5° and so only reaches ground level very far downstream.

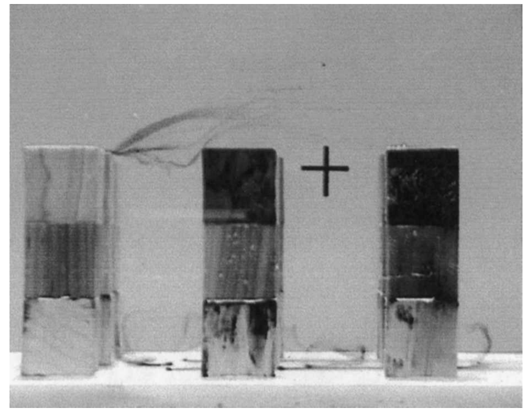

FIG. 8. Visualization of dye streaks showing the three-dimensional nature of the rooftop-level shear layer for $H/w_b = 3$. Also evident at ground level is downstream flow in the street canyon and upstream flow in the region of the building wake.

Comparison shows that a better fit to the hyperbolic tangent profile resulted from a value of the fraction of $a = 5$, especially at vertical height $(z - H)a/\Delta z_{\mathrm{SL}} \sim 2.5$ (corresponding to $z/H \sim 1.65$). The velocity fields at locations $x/B = 3$ and $x/B = 10$ are not yet fully developed and so do not fit the hyperbolic tangent form well. It is evident that the profiles from $x/B = 22$ to $x/B = 38$ collapse well onto Eq. (1), thus providing a way to estimate the mean velocity in and above the urban canopy. [Given field data of mean wind velocity U, the use of Eq. (1) and Fig. 9 (described in detail below) forms an algorithm for collapsing mean velocity data usefully.] Velocity profiles for plant canopies of the form of Eq. (3.34) in Kaimal and Finnigan (1994), $\overline{u}/\overline{u}_{\mathrm{hc}} = \exp[-\nu_e(1 - z/h_c)]$, were also found to provide a reasonable fit to the data within the Hwb3 canopy (here the parameters h_c, u_{hc}, and ν_e are the plant canopy height, velocity at canopy height, and extinction coefficient, respectively). However, the profiles are sensitive to the value of the extinction coefficient, which is not known a priori.

The shear layer produced by the canopies are very different for $H/w_b = 1$ and $H/w_b = 3$, though both grow vertically (thicken) with distance (Fig. 7). The principal difference is that the shear layer for Hwb1 urban canopy exists from well above the building height all the way to ground level, whereas for Hwb3 urban canopy the shear layer extends from just above the building height to about one-half of the building height far downstream. No data exist for the Hwb1 urban canopy below $z/H = 0.3$ because of the limited (optical) spatial resolution near the ground level, but visual observations showed that the shear layer reaches all the way to the ground level. The difference in shear-layer thickness and the extension of the Hwb1 urban canopy shear layer to the ground level has important implications regarding rates of dispersion. In the event of a rooftop release for Hwb1, releases will reach ground level quickly; this will not be the case for Hwb3, for which the shear layer is elevated above the ground for long distances. This also suggests that a ground-level release will dilute more rapidly for Hwb1 than for Hwb3.

Kelvin–Helmholtz (KH) instabilities were not observed in either urban canopy despite extensive flow visualization attempts. Flow visualization showed that the flow in the vicinity of the building height was three-dimensional; thus, the shear layer of urban canopies is not susceptible to KH instability. Figure 8 is a visualization of the flow for the Hwb3 urban canopy, arising from 8 s of video data. Evident is the three-dimensional nature of the flow at the rooftop level. Dye streaks are seen both to rise above the buildings and to descend below the rooftop level; the thickness of the ascending dye streak is greater than the descending dye streak, suggesting that the former occurs more frequently. At the ground level the visualization shows that the flow is downstream in the street canyon but upstream in the region of the building wake. (Also evident is the vertical transport of the dye streak in the building wake.) For the Hwb1 urban canopy the vertical growth rate of the shear layer is 6° in the vicinity of the rooftop level; for a Hwb3 urban canopy the overall vertical growth rate of the shear layer is approximately 7.5° (see Fig. 7). The angles of spread for both Hwb1 and Hwb3 urban canopies are thus smaller than the observations by Brown and Roshko (1974) of a two-dimensional shear layer, where KH instabilities resulted in a shear layer that grew at 12°. The smaller growth rates for the urban canopies are likely due to the three-dimensional nature of the flow. The smaller angles of spread of the shear

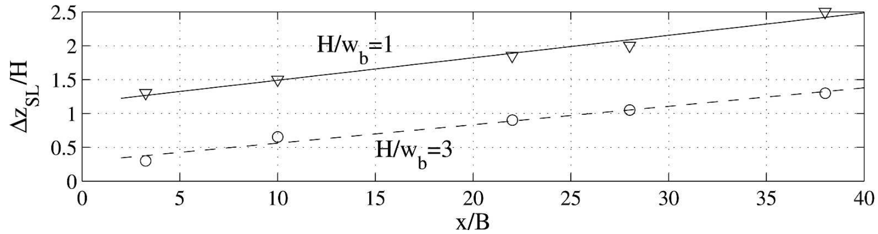

FIG. 9. Longitudinal evolution of nondimensional shear-layer thickness for Hwb1 and Hwb3 urban canopies. Best-fit lines to data are valid for downwind distances $x/B \geq 3$.

layer of urban canopies in comparison with the KH shear-layer angles of spread are in keeping with Squire's theorem, which says that two-dimensional disturbances grow faster than three-dimensional disturbances (Kundu and Cohen 2004).

Evolution of the nondimensional shear-layer thickness $\Delta z_{SL}/H$ for Hwb1 and Hwb3 urban canopies shows a linearly increasing trend with distance x/B for both cases (Fig. 9). The best-fit linear line describing the observed shear-layer thickness for the Hwb1 urban canopy is $\Delta z_{SL}/H = 0.03(x/B) + 1.17$; for Hwb3 urban canopies the best-fit linear line is $\Delta z_{SL}/H = 0.025(x/B) + 0.3$. Note that both formulas apply for downwind distances $x/B \geq 3$. In general, the shear-layer thickness for an Hwb1 urban canopy is 2 times the shear-layer thickness for an Hwb3 urban canopy.

To facilitate comparison with field data and numerical simulations of urban canopies, data are presented in Fig. 10 of nondimensionalized values of shear, where the horizontal scale is normalized by w_b/U_b. Large values of nondimensional shear are 0.9 and 0.8 for Hwb1 and Hwb3 urban canopies, respectively, at rooftop levels. Maximal values of nondimensional shear ~1 occur close to ground level for both canopies.

The structure of the shear profile for the Hwb1 urban canyon is approximately uniform for both below the building height ($dU/dz \sim 1.75$ s^{-1}) and above the building height ($dU/dz \sim 0.5$ s^{-1}). For the Hwb3 urban canopy, the structure is different in that there are large, localized shears at the building height ($dU/dz \sim 2$ s^{-1}) and close to ground level ($dU/dz \sim 2.3$ s^{-1}). Just below the rooftop level for Hwb3, urban canopy values of shear are about 0.5 s^{-1}, and above rooftop level the shear decreases from 0.75 s^{-1} to zero with increasing height. Note that the shear also diminishes to zero at the building midheight $z/H \sim 0.5$. An overall perspective of the structure of the flow in and above the urban canopy is that of a shear layer whose thickness grows vertically with downstream distance as shown in Fig. 7. However, the broad overall shear layers shown in Fig. 7 should not be thought of as homogeneous layers of shear but should be considered as compound shear layers with regions of low and high shear.

4. Conclusions

Laboratory results establish that important differences can occur in the mean flow characteristics of flow above and in urban canopies; flow characteristics depend on the aspect ratio H/w_b of the urban canopies, as

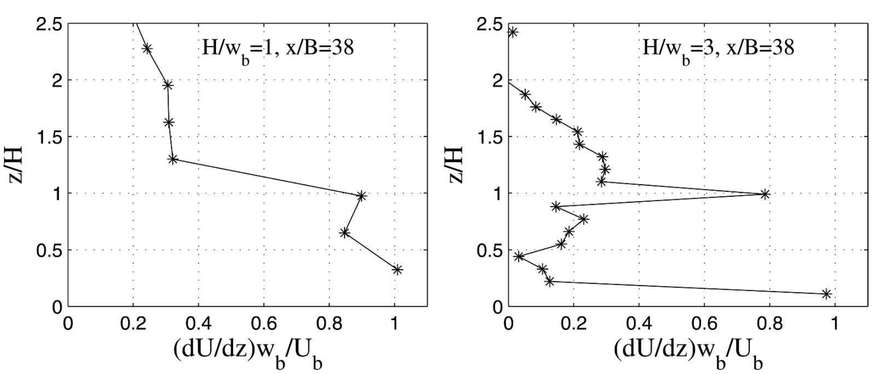

FIG. 10. Vertical profiles of nondimensional shear $(dU/dz)w_b/U_B$ for Hwb1 and Hwb3 urban canopies. Data shown are collected at a distance $x/B = 38$. Note the sharp extrema of shear at building height and ground level for the Hwb3 urban canopy. The profile for the Hwb1 urban canopy is approximately uniform above and below the building height. Note that the extremal values of nondimensional shear are ~1.

well as the areal densities λ_f and λ_p. The mean velocity profile for urban canopies with $H/w_b = 1$ resembles a power-law boundary layer that evolves with downwind distance x. Because of the longitudinal evolution, the profiles generally cannot be fitted to a single power-law index. For urban canopies with $H/w_b = 3$, the mean velocity profile resembles a shear layer with an inflection point located near the building height. The mean velocity profiles for the Hwb3 urban canopy also evolve with distance x and fit well to the hyperbolic tangent profile described by Eq. (1).

A shear layer, defined as the vertical extent of the linear region of the mean velocity profile, exists in the vicinity of the building height. Analysis reveals major differences in the form of the near-rooftop-level shear layer for urban canopies with aspect ratios $H/w_b = 1$ and $H/w_b = 3$. This shear layer thickens with distance x/B for both cases. For an Hwb1 urban canopy the shear layer extends from well above the urban canopy to ground level, whereas for the Hwb3 urban canopy the shear layer remains elevated above the ground, extending from just above the building height to about building midheight far downstream. Values of nondimensional shear-layer thickness $\Delta z_{SL}/H$ for Hwb1 urban canopies are generally 2 times that of Hwb3 urban canopies. The differences of magnitude of shear, location, and vertical extent of shear layers for urban canopies of aspect ratios $H/w_b = 1$ and $H/w_b = 3$ have important implications for the rates of dispersion in and above such urban canopies. In the event of a ground-level release, the release is likely to disperse more rapidly for an urban canopy of Hwb1 than for an urban canopy of Hwb3; in the event of a rooftop release, the release will reach ground level faster for an Hwb1 urban canopy than for an Hwb3 urban canopy.

Measured values of shear dU/dz differed for Hwb1 and Hwb3 urban canopies. For an urban canopy with Hwb1, shear values are constant above and below the building height [~0.5 and ~1.75 s^{-1}, corresponding to nondimensional values of 0.3 and 0.9 $(dU/dz)w_b/U_b$, respectively]. For an urban canopy with Hwb3, large, localized peaks of shear occur at rooftop and ground levels [~2 and ~2.3 s^{-1}, corresponding to nondimensional values of 0.8 and 1 $(dU/dz)w_b/U_b$, respectively]. At building midheight, shear diminishes to zero, and just above and below rooftop level the average value of shear is about 0.5 s^{-1} for Hwb3 urban canopies. Detailed analysis of the mean velocity profiles and mean velocity gradients indicates that for each canopy the shear layer is not a homogeneous layer with one value of velocity gradient dU/dz but rather is a compound shear layer with larger values of dU/dz at rooftop levels. Peak values of shear are located at $0.9 < z/H < 1.1$ for Hwb3 urban canopy, which is in the middle of the overall shear layer. The compound shear structure is still evident, though not as pronounced for an urban canopy with $H/w_b = 1$. Shear, nondimensionalized by the quantity w_b/U_b, has peak values ~1 close to ground levels for both canopies; this normalization does not change the structure of dU/dz values but enables further comparisons with field studies.

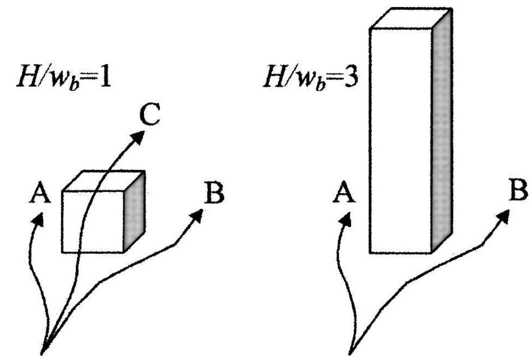

FIG. 11. Schematic of idealized streamlines of turbulent flow around and above buildings for Hwb1 and Hwb3 urban canopies. For a fluid particle located at ground level upstream of a building, more advective pathways are available for the Hwb1 urban canopy in comparison with the Hwb3 urban canopy. A consequence is that larger rates of ground-level dispersion rates are possible for the Hwb1 urban canopy.

Consideration of possible pathways of a fluid particle located at ground level, in a turbulent flow, upstream of a building is helpful in discriminating differences in dispersion scenarios between urban canopies with differing aspect ratios H/w_b (see Fig. 11). For the Hwb1 urban canopy, the shear layer reaches all the way to ground level, and both horizontal and vertical advective pathways (A, B, and C) are possible, whereas only horizontal pathways A and B arise for the Hwb3 urban canopy. A consequence is that larger rates of ground -level dispersion are likely for the Hwb1 urban canopy. Implications of the different characteristics of the shear layer in and above urban canopies with varying aspect ratios H/w_b are profound. Cities with urban canopies with $H/w_b = 1$, such as LA, are likely to be better ventilated at ground level when compared with midtown NYC (i.e., Manhattan, for which $H/w_b = 3$). Thus, dispersion coefficients at the ground level are likely to be greater in midtown LA than in midtown NYC.

Acknowledgments. Financial support from the DuPont Company is gratefully acknowledged.

REFERENCES

Britter, R. E., and S. R. Hanna, 2003: Flow and dispersion in urban areas. *Annu. Rev. Fluid Mech.,* **35,** 469–496.

Brown, G. L., and A. Roshko, 1974: On density effects and large structure in turbulent mixing layers. *J. Fluid Mech.,* **64,** 775–816.

Brown, M. J., R. Lawson, D. DeCroix, and R. Lee, 2000: Mean flow and turbulence measurements around a 2-day array of buildings in a wind tunnel. Preprints, *11th Joint Conf. on the Applications of Air Pollution Meteorology with the Air and Waste Management Association,* Long Beach, CA, Amer. Meteor. Soc., 35–40.

——, H. Khalsa, M. Nelson, and D. Boswell, 2004: Street canyon flow patterns in a horizontal plane: Measurements from the Joint Urban 2003 field experiment. Preprints, *Fifth Symp. on the Urban Environment,* Vancouver, BC, Canada, Amer. Meteor. Soc., CD-ROM, 3.1. [Available online at http://ams.confex.com/ams/AFAPURBBIO/techprogram/session_16806.htm.]

Counihan, J., 1969: An improved method of simulating an atmospheric boundary layer in a wind tunnel. *Atmos. Environ.,* **3,** 197–214.

Dobre, A., S. J. Arnold, R. J. Smalley, J. W. D. Boddy, J. F. Barlow, A. S. Tomlin, and S. E. Belcher, 2005: Flow field measurements in the proximity of an urban intersection in London, UK. *Atmos. Environ.,* **39,** 4647–4657.

Finnigan, J. J., 2000: Turbulence in plant canopies. *Annu. Rev. Fluid Mech.,* **32,** 519–571.

Ghisalberti, M., and H. M. Nepf, 2002: Mixing layers and coherent structures in vegetated aquatic flows. *J. Geophys. Res.,* **107,** 3011, doi:10.1029/2001JC000871.

Hall, D. J., R. Macdonald, S. Walker, and A. M. Spanton, 1996: Measurements of dispersion within simulated urban arrays—A small scale study. BRE Client Rep. CR 178/96.

Ho, C., and P. Huerre, 1984: Perturbed free shear layers. *Annu. Rev. Fluid Mech.,* **16,** 365–424.

Jackson, P. S., 1981: On the displacement height in the logarithmic velocity profile. *J. Fluid Mech.,* **111,** 15–25.

Jimenez, J., 2004: Turbulent flows over rough walls. *Annu. Rev. Fluid Mech.,* **36,** 173–196.

Kaimal, J. C., and J. J. Finnigan, 1994: *Atmospheric Boundary Layer Flows: Their Structure and Measurement*. Oxford University Press, 289 pp.

Kastner-Klein, P., and M. W. Rotach, 2004: Mean flow and turbulence characteristics in an urban roughness sublayer. *Bound.-Layer Meteor.,* **111,** 55–84.

Kundu, P. K., and I. M. Cohen, 2004: *Fluid Mechanics*. 3d ed. Elsevier, 484 pp.

MacDonald, R. W., R. F. Griffiths, and D. J. Hall, 1998: An improved method for the estimation of surface roughness of obstacle arrays. *Atmos. Environ.,* **32,** 1857–1864.

Meroney, R. N., 1990: Fluid dynamics of flow over hills/mountains—Insights obtained through physical modeling. *Atmospheric Processes over Complex Terrain, Meteor. Monogr.,* No. 45, Amer. Meteor. Soc., 145–171.

Oke, T. R., 1987: *Boundary Layer Climates*. 2d ed. Routledge, 435 pp.

Raupach, M. R., J. J. Finnigan, and Y. Brunet, 1996: Coherent eddies and turbulence in vegetation canopies: The mixing layer analogy. *Bound.-Layer Meteor.,* **78,** 351–382.

Rotach, M. W., 1995: Profiles of turbulence statistics in and above an urban canyon. *Atmos. Environ.,* **29,** 1473–1486.

——, and Coauthors, 2005: Bubble—An urban boundary layer meteorology project. *Theor. Appl. Climatol.,* **81,** 231–261.

Roth, M., 2000: Review of atmospheric turbulence over cities. *Quart. J. Roy. Meteor. Soc.,* **126,** 941–990.

Schatzmann, M., and B. Leitl, 2002: Validation and application of obstacle-resolving urban dispersion models. *Atmos. Environ.,* **36,** 4811–4821.

Shaw, R. H., R. H. Silversides, and G. W. Thurtell, 1974: Some observations of turbulence and turbulent transport within and above plant canopies. *Bound.-Layer Meteor.,* **5,** 429–449.

Yee, E., D. J. Wilson, and B. W. Zelt, 1993: Probability distributions of concentration fluctuations of a weakly diffusive passive plume in a turbulent boundary layer. *Bound.-Layer Meteor.,* **64,** 321–354.