DISPERSION LENGTH SCALES WITHIN AND ABOVE THE URBAN CANOPY

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1. INTRODUCTION

Difficulties arise in numerical modeling because the flow over and within the urban environment is a complex boundary layer flow; essentially, the flow field is a boundary layer for which the roughness elements (i.e. buildings) are as tall as the overall height of the urban boundary layer. Little is known about such very rough boundary layers. Air flow in the urban environment differs from boundary layer flows over flat terrain or rolling hills in that flow past buildings is strongly perturbed (or broken up). A syndrome of the urban environment is complex interactions of the flow between buildings. Of dynamical significance are length scales reflecting building geometry, arrangement of buildings, as well as additional length scales relevant to groups of similar buildings (i.e. neighborhoods). As such length scales are site specific and vary within neighborhoods, and as the details and geometry of neighborhoods and ultimately cities differ, it has been difficult to develop general guidelines for predictive analysis. In this study we report the results of laboratory experiments with a continuous ground level point source undertaken on two model urban canopies with different building aspect ratios. Comparison of results shows the relevant scales that control dispersion in model urban canopies.

2. EXPERIMENTS

Laboratory measurements were undertaken in a water tunnel at the Environmental Fluids Lab at the University of Delaware. The Plexiglas water tunnel is 400 cm long, 40 cm deep, and 25 cm wide. The Plexiglas walls enable the use of flow visualization techniques, and a free surface allows measurements to be made with micro-conductivity probes. Two uniform canopies of height H = 3.2 cm and H = 9.6 cm and building width w_b = 3.2 cm were utilized for the experiments. Thus the building aspect ratios of the two model urban canopies are H/w_b of 1 and 3, defining shallow and deep canyons, respectively. The canopies consist of 22 rows of three 3.2 cm square buildings, with lateral spacing S = 3.5 cm and longitudinal spacing G = 5 cm. For the above parameters, the areal densities known as the lambda parameters λ_p and λ_f, the plan area density and the frontal area density respectively, are given by

$$\lambda_p = w_b B/((w_b + G)(B + S)) \quad (1)$$

$$\lambda_f = w_b H/((w_b + G)(B + S)) \quad (2)$$

where B is the length of the building (along the x-axis). Values of the lambda parameters are $\lambda_p = \lambda_f = 0.19$ for the H/w_b = 1 urban canopy; $\lambda_p = 0.19$ and $\lambda_f = 0.56$ for the H/w_b = 3 urban canopy. We define the space between the buildings in a longitudinal direction as the urban canyon. Velocity and scalar measurements were taken along the centerline of the urban canyon in the x-z plane. Velocity measurements were determined using particle image velocimetry (PIV). Mean and rms fluctuating velocities [U, u', w'] were determined from the time series of the flow recorded on video.

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3. DISPERSION MODEL

We use the Gaussian plume model presented in Franzese and Huq 2011 to provide a baseline analytical representation of dispersion. The mean concentration field c of a tracer emitted from a ground-level continuous source is approximated by a reflected Gaussian formula,

$$C = \frac{Q}{\pi U \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right) \quad (3)$$

$$\sigma_y^2 = \sigma_{yo}^2 + \sigma_v^2 t^2 \quad (4)$$

$$\sigma_z^2 = \sigma_{zo}^2 + b^2 \sigma_w^2 t^2 \quad (5)$$

where y indicates the crosswind direction and the source is located at y = 0, σ_y and σ_z are the standard deviations of the crosswind and vertical distributions of concentration, respectively, σ_{yo} and σ_{zo} are the standard deviations at the source, b is an empirical constant (b = 1 for daytime atmosphere, and b = 0.5 for nighttime atmosphere), and U is the mean wind speed across the plume.

Equation (4) is written according to the near-field approximation of Taylor (1921), assuming an exponentially decaying velocity correlation function. Equation (5) was derived by Hunt and Weber (1979) for ground-level releases in a neutral-boundary layer. The empirical constant b = 1. In this paper we utilize the same model to represent dispersion when the plume generated by a ground level source resides mostly below the mean canopy height. The ratio σ_v/U has been obtained by best fit to the experimental data. Then, U is estimated by best fit of Eq. (3) to the observed concentrations. Finally, the relationship $\sigma_w = 2\sigma_v/3$ has been assumed, as reported by Roth (2000), Hanna et al. (2007), and Franzese and Huq (2011).

4. MODEL SETTINGS

Summary of relevant flow and turbulence characteristics used in the model are given in Table 1. $L_z = H$ and $L_y = G/2$ are the vertical and horizontal turbulence length scales within the canopy, $T_z = L_z/\sigma_w$ and $T_y = L_y/\sigma_v$ are the vertical and horizontal turbulence time scales, respectively.

5. HORIZONTAL AND VERTICAL PLUME SPREADS AND MODEL COMPARISONS

Growth rates of σ_y/L_y and σ_z/L_z as functions of the non dimensional distance x/UT, along with the predictions of Eqs. (4) and (5) are shown in figure 1. The non-dimensional

Table 1: Summary of relevant flow and turbulence characteristics used in the model. L_z and L_y are the vertical and horizontal turbulence length scales within the canopy, $T_z = L_z/\sigma_w$ and $T_y = L_y/\sigma_v$ are the vertical and horizontal turbulence time scales, respectively. U is the in-canopy wind speed.

	H (cm)	σ_w (cm s^{-1})	σ_v (cm s^{-1})	T_z (s)	T_y (s)	L_z (cm)	L_y (cm)	U_∞ (cm s^{-1})	U (cm s^{-1})
$H/w_b = 1$	3.20	0.21	0.31	15.46	5.64	3.20	1.75	9.40	2.7
$H/w_b = 3$	9.60	0.15	0.22	64.29	7.81	9.60	1.75	11.00	2.8

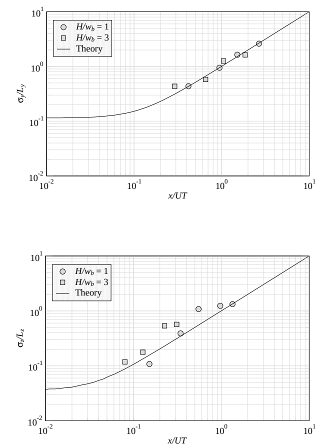

FIG. 1: Growth rates of σ_y/L_y and σ_z/L_z as functions of the non dimensional distance x/UT, along with the predictions of Eqs. (4) and (5)

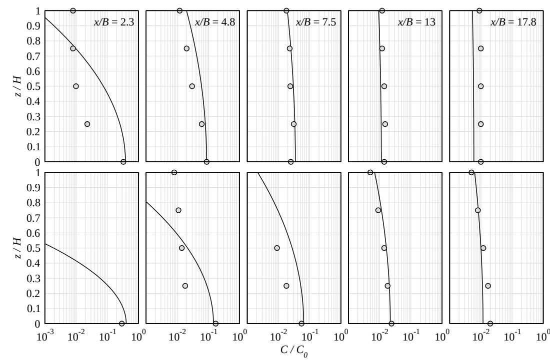

FIG. 2: Profiles of concentration for the short (top panels) and the tall canopy (bottom panels). Measurements taken at the canyon centerline, at the distances reported in the figure. The solid line is the model prediction (Eq. 3). Data normalized by the source concentration C_0.

data for both canopies collapse well and describe linear plume growth in accordance with Eqs. (4) and (5), providing support for the appropriate choice of the length scales L_y and L_z.

Profiles of concentration normalized by the source concentration C_0 for the short and the tall canopy are shown in figure 2. The measurements were taken at the canyon centerline, at the distances reported in the figure.

Predicted vs. observed centerline ground-level non-dimensional concentration C/C_0 and centerline ground-level non-dimensional concentration CUL_yL_z/Q as a function of non-dimensional distance x/UT is reported in figure 3. The data for both canopies collapse well using this type of non-dimensionalization for C and for x.

6. ACKNOWLEDGEMENTS

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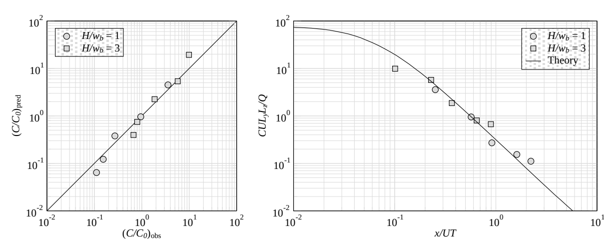

FIG. 3: Left panel - Predicted vs. observed centerline ground-level non-dimensional concentration C/C_0. Right panel - Centerline ground-level non-dimensional concentration CUL_yL_z/Q as a function of non-dimensional distance x/UT