WIND DRIVEN RAIN DISTRIBUTIONS
AROUND STREET CANOPIES¹*Tsang-Jung Chang and Yu-Ting Wu²*

ABSTRACT: Wind driven raindrop tracking is used to investigate the microscale redistribution of wind driven rainfalls in street canopies by combining a Eulerian wind flow model and a Lagrangian raindrop tracking model. The former conducts large eddy simulations of the turbulent flows in street canopies, and the latter performs raindrop trajectory calculations by releasing a large number of raindrops into the computational domain. The wind speed model is verified with available wind tunnel measurement. Twenty sets of simulations are carried out for various building configurations and driving rain angles. The simulated results show that the trajectories of smaller raindrops are more slanting and more influenced by the multibuilding perturbed flow field. Impingement of raindrops on the building envelope increases from bottom to top. The height of the front building is a significant factor affecting wind driven rain redistribution. Distinct nonuniform spatial rainfall distributions are found for scenarios with high building configurations and low driving rain angles. The simulated results are further integrated to assess the effect of real raindrop size distributions by weighing the volumetric fraction of a range of drop sizes. There is about 10 percent variation in spatial extent of street canopies. An overall 5 to 17.4 percent increase of the rainfall amount in the upwind zone is observed.

(**KEY TERMS:** urban storm water management; wind driven rain; hydrometeorology; raindrop trajectory; street canopy; computational fluid dynamics.)

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INTRODUCTION

As raindrops fall through the atmospheric boundary layer over rugged terrain, rainfall distributions are affected by the topography perturbed wind field. Two distinct mechanisms affecting topography induced rainfalls, namely the meso local scale (10^3 -

10^5 m of horizontal distance scale) and the micro scale (10^{-2} - 10^3 m of horizontal distance scale), are well known (Oke, 1987). The meso local scale mechanism, studied by many meteorologists, is associated with the altitude related increase or decrease of rainfalls on windward or leeward slopes. It results from the rain forming processes by either enhancing or suppressing the conversion of cloud water to rainwater. The microscale mechanism involves the effect of locally perturbed wind fields (e.g., by buildings, small hills, shelter belts) on the redistribution of raindrops before they reach the ground and does not take the rain forming processes into consideration. From the viewpoint of storm sewer system design, the meso local scale mechanism can be addressed by analyzing integrated networks of rain gauge stations near the study site. On the other hand, due to limited rain gauge stations situated in a microscale area, the microscale mechanism cannot be clearly understood by using the same procedure. As a result, it is useful to conduct further numerical modeling or field experiments of the microscale mechanism.

Many metropolitan cities are characterized by clusters of tall buildings, narrow streets, and trees. The air flow patterns in urban areas are extremely complex. Redistribution of wind driven rainfalls in urban areas strongly depends on raindrop trajectories in street canopies. In the absence of wind, raindrops fall vertically downward with terminal fall velocity, resulting in a spatially uniform rainfall distribution on the street surfaces and building roofs (Figure 1a). For raindrops in windy open terrains, one can expect that raindrops follow curved paths, which are determined by their own weight (or the raindrop terminal fall velocity) and the drag force exerted on the droplet

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by the wind (or the inflow unobstructed wind velocity) and finally impinge on the ground with a horizontal drift (Figure 1b), also resulting in a uniform rainfall distribution. The ratio of the raindrop terminal fall velocity to the unobstructed horizontal wind velocity is herein defined as the driving rain angle, which characterizes vertical momentum to horizontal momentum of a raindrop. For the regions in the vicinity of street canopies (Figure 1c), raindrop trajectories are affected not only by the driving rain angle, but also by the particular flow field surrounding street canopies including turbulent boundary layer, stagnation region, flow separation, cavity circulation, curved

streamlines, sharp pressure gradients, anisotropic turbulence, reattachment, and vortex shedding. Just as a raindrop reaches a terminal fall velocity in still air, a raindrop in the wind reaches the constant horizontal velocity equal to the wind velocity. The only difference is that the wind flow field in street canopies is continually changed so that the raindrop horizontal velocity continually varies. The corresponding rainfall distribution around street canopies is thus no longer spatially uniform. To understand wind driven rainfall redistributions around street canopies, numerical modeling of the trajectories and terminating positions of wind driven rains is essential.

Figure 1. Wind Driven Rain Trajectories in (a) Windless Open Terrain, (b) Windy Open Terrain, and (c) Windy Street Canopies.

Several researchers have developed various numerical models or have conducted field observations to investigate wind-driven rain trajectories around buildings (Lacy, 1951, 1965; Choi, 1993, 1994, 1999; Surry *et al.*, 1994; Lakehal *et al.*, 1995; Karagiozis *et al.*, 1997). All of these works focused on the influence of wind driven rain on façades of a single building for preventing water damage to wall systems and interiors of buildings, especially the front face of a building. Little attention has been paid in the literature to evaluating the microscale redistribution of wind driven rainfalls in urban areas with multiple buildings, from the viewpoint of the storm water drainage system design. As civil engineers make use of more sophisticated building layouts, there is an increasing need for more detailed information about rainfall redistribution around the buildings. Therefore, the main objective of the study reported in this paper is to develop a numerical methodology to carry out a series of scenario simulations of wind driven rain trajectories and terminating positions around two-dimensional (long) street canopies so that one can quantitatively investigate the effects of building configurations and driving rain angles on rainfall distributions. The numerical methodology includes a Eulerian wind flow model and a Lagrangian raindrop tracking model. The spatial distribution of wind driven rainfalls around street canopies for each scenario is evaluated as well.

METHODOLOGY OF MODELING

The numerical methodology for simulating the transport and deposition patterns of raindrops around street canopies consists of two parts, the Eulerian wind flow model around street canopies and the Lagrangian raindrop tracking model. The wind flow model conducts the large eddy simulation of the Eulerian turbulent flows around street canopies, which is solved first to obtain the velocity and pressure distributions. The result of the velocity distribution is next input to the Lagrangian raindrop tracking model to calculate the velocities and trajectories of individual raindrops by tracking a large number of raindrops in the computational domain.

Eulerian Wind Flow Around Street Canopies

The wind flow around street canopies is usually considered to be incompressible turbulent Eulerian flow and is herein simulated by the large eddy simulation (LES). The principle of LES is that the

turbulent flow is filtered to remove small scale eddies and leave large scale turbulence. The large scale turbulence is solved explicitly by computing the filtered equations numerically. The influence of the filtered scales below cannot be neglected and this influence leads to the subgrid stresses (SGS). Let $\bar{u}_i$ and p be the spatially filtered velocity component in the x_i direction and pressure, respectively. The bar represents grid filtering. The continuity equation and the equations of motion for the filtered velocities $\bar{u}_i$, with an eddy viscosity representation for the subgrid stresses, are

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

and

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} \left(\nu_{sgs} \frac{\partial \bar{u}_i}{\partial x_j} \right) \quad (2)$$

where ρ is the fluid density, ν is the fluid kinematic viscosity and ν_{sgs} denotes the subgrid eddy viscosity. A subgrid model based on an eddy viscosity closure is used so that ν_{sgs} is taken to be proportional to the numerical grid size and the subgrid energy as

$$\nu_{sgs} = (C_s \Delta)^2 \left[\frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)^2 \right]^{1/2} \quad (3)$$

in which $\Delta = (\Delta x_i \Delta x_j)^{1/2}$ is the numerical grid size defined by the geometric average of the finite difference grid space in three directions. C_s is the Smagorinsky constant and usually has a value between 0.1 and 0.2. In this case it has a value of 0.15. ν_{sgs} decreases as C_s becomes smaller, reflecting smaller scales of turbulence.

The above governing equations are solved numerically on a staggered mesh system for the velocity and pressure quantities. The numerical scheme uses a third-order upwind finite difference scheme for the convective terms and a second-order central finite difference scheme for others. The Adams-Bashforth method is used for the finite difference in time. The pressure Poisson equation is solved using an iteration method on the staggered mesh. Several types of the boundary conditions are used in the present research. At the inflow boundary, the power law velocity is specified, and it remains unchanged with time. No slip velocity boundary conditions are applied to all solid surfaces and ground. At the outflow and upper boundaries, the velocity gradient is set at zero. The initial

conditions of the velocity fields are set at zero in the entire computational domain.

It should be pointed out that since the above LES produces time dependent solutions, the time averaged wind velocities $\langle \bar{u}_i \rangle$ can be obtained by statistical analysis of the spatially filtered velocities $\bar{u}_i$ according to

$$\bar{u}_i = \langle \bar{u}_i \rangle + \bar{u}_i'$$

in which $\bar{u}_i'$ denotes the turbulent components of the filtered velocities. In the present study, the time averaged velocity is determined by statistics over a time period using 200 instantaneous velocity samples, equally spaced in time.

Lagrangian Raindrop Trajectories Around Street Canopies

Rain trajectories are determined based on an instantaneous force balance between the aerodynamic drag and the submerged gravitational force on the raindrop in the wind field as

$$M \frac{du_i^p}{dt} = \frac{\pi}{8} \rho C_D d_p^2 (\bar{u}_i - u_i^p) \sqrt{\sum (\bar{u}_i - u_i^p)^2} - M \delta_{i3} g \quad (5)$$

and

$$\frac{dx_i^p}{dt} = u_i^p \quad (6)$$

where M is the submerged rain drop mass, $\bar{u}_i$ is the instantaneous filtered wind velocity in x_i direction, u_i^p is the raindrop velocity in x_i direction, x_i^p is the raindrop displacement in x_i direction, t is the time, g is the gravitational acceleration, d_p is the raindrop diameter, ρ_p is the raindrop density, R_e is the sphere

Reynolds number $\left(= d_p \sqrt{\sum (\bar{u}_i - u_i^p)^2} / \nu \right)$, and C_D is the droplet drag coefficient. C_D is a function of R_e , obtained from the empirical formulas for drag on a droplet (Gunn and Kinzer, 1949). With $\bar{u}_i$ around street canopies known, Equations (5) and (6) are solved using the fourth-order Runge-Kutta algorithm to calculate the velocities and trajectories of individual raindrops at each time step. Individual raindrops are tracked from the release point until the computational boundary is reached or some integration limit criterion is met.

Trajectories of individual raindrops are then used to calculate wind driven rainfall distribution around street canopies. Since the raindrop drag coefficient is a function of the raindrop diameter, raindrops with different diameters should have different patterns of trajectories. It should be noted that raindrop evaporation and breakup are not considered in the present research. It is assumed that individual raindrop has a spherical shape, and its diameter remains constant at its initial value. It is reasonable to further assume that there is no influence of raindrops on the surrounding turbulent flow and no raindrop-to-raindrop interaction, because the measured volume fraction of rainwater in the air for a rainfall of 10 mm/hour intensity is only 5×10^{-7} (Gunn and Kinzer, 1949).

MODEL VERIFICATION

Before applying the present model to the scenario simulations of the proposed problem, the model is verified with a wind tunnel measurement of street canopies (Gerdes and Olivari, 1999), which provides reliable data of wind velocity around the street canopies. In addition, the street canopy configuration used by them is very similar to the building configuration in our proposed problem. However, the raindrop trajectory model is not herein verified because no experimental data are available in the literature. The wind tunnel was 2 m in length and 0.34 m in height. Two parallel metal walls were used to constitute the two-dimensional street canopy. The upstream wall was $H_u = 0.03$ m high and 2 mm thick, whereas the downstream wall was $H_d = 0.05$ m high and 2 mm thick. The gap between the two walls was 0.045 m. The free stream velocity of the incoming boundary layer flow was 1.7 m/s. The corresponding Reynolds number based on the height of the upstream wall was 3400. Sensitivity analysis indicated that the flow characteristics do not change for much higher Reynolds numbers (Xia and Leung, 2001). The average velocity distribution inside the street canyon was measured. Figure 2 depicts the simulated wind velocity field in the street canyon (the area between two buildings). Due to the blockage effect of the tall downstream wall, a strong clockwise vortex exists inside the street canyon to drive the entrained air at the upwind face of the tall wall (high pressure zone) clockwise to the downwind face of the lower wall (low pressure zone). The maximum velocity is about 1 m/s. These flow patterns are consistent with the measured data. The velocity fields of other configurations of street canopies measured by Gerdes and Olivari, not presented here, were also verified to check the model's accuracy.

Figure 2. Model Verification With Available Measured Data.

SCENARIO SIMULATIONS

As stated previously, wind driven rain trajectories around street canopies are governed by the driving rain angle and the flow field surrounding street canopies. As a result, under a given boundary layer inflow, various street canopy configurations and driving rain angles can cause different raindrop trajectories and terminating positions, resulting in different levels of microscale rainfall variations. Figure 3 presents the five types of two-dimensional street canopies investigated in the scenario simulations. They are very common in many metropolitan cities and hereby simulated with two parallel rectangular buildings of different heights. The front and rear buildings are all 40 m in length, and the distance between them is also 40 m. The inflow velocity distribution is power law, $U = U_r(z/z_r)^{0.299}$, where $z_r = 10$ m and U_r is the inflow unobstructed velocity. U_r is set at 5 m/s for all cases, which is a common average wind speed of thunderstorms in Taiwan. Four driving rain angles are simulated for each type of street canopy. Detailed information of the 20 numerical scenarios is summarized in Table 1. All scenario simulations assume an isothermal condition with domain temperature of 20°C.

The computational domain is from 10W upstream of the front building to 15W downstream of the rear building in the streamwise direction and from the ground surface to 8W in the vertical direction, where $W = 40$ m denotes the distance between the two

buildings. A nonuniform grid system of 601*301 grids is used. The total grid number is about 180,000. Starting from the building walls, the horizontal grid interval increases uniformly both in the upstream and downstream directions, and the vertical grid interval increases upward to the upper boundary.

Flow Patterns Around Street Canopies

The simulated time averaged wind velocity fields of the five types of street canopies (see Figure 3) are illustrated in Figure 4. The Reynolds number is about 10^7 based on the highest height of the buildings and the inflow wind velocity. As demonstrated by Oke (1987), the flow regimes around street canopies can be classified into three categories: isolated roughness, wake interference, and skimming flows, according to the ratios of the building height to the distance between buildings. In Figure 4, the Type I street canopy is a typical example of the purely boundary-layer wind field. The other four types of street canopies can be categorized as the skimming flow pattern. It can be observed from Figure 4 that the skimming flow field surrounding street canopies includes a small clockwise vortex in front of the front building, a closed clockwise recirculating eddy inside the street canyon, and a large wake zone in the back of the rear building. Because of the blockage effect due to the front building, there is a speed up of the wind sweeping upward around the top of the building, a slow down of the wind upstream of the front building, and a stagnation region in between. The blockage effect is more significant as the height of the front building increases. Inside the canyon, the combined blockage effect of the front and the rear buildings results in a closed circulation zone with reduced wind velocity on the order of 10 percent of the inflow unobstructed velocity. The recirculating eddy becomes stronger as the height of the rear building increases, whereas it becomes weaker as the height of the front building increases. After the eddy passes over the rooftop of the rear building, a large wake zone is formed in which a large clockwise recirculation region and a counterclockwise vortex below the recirculation region can be seen.

Turbulent Dispersion of Raindrop Trajectories

Equations (5) and (6) indicate that the raindrop trajectory depends on the instantaneous filtered wind velocity, which is a random process and is usually categorized by the time averaged wind velocity and the turbulent fluctuation velocity. To understand raindrop

Figure 3. Schematic Diagram of the Scenario Simulations (a) Type I, (b) Type II, (c) Type III, (d) Type IV, and (e) Type V Street Canopy.

TABLE 1. Summary of the Street Canopy Scenarios.

Scenario	Street Canopy Type	Building Height (m)		Raindrop Diameter d_p (mm)	Raindrop Fall Velocity, U_T (m/s)	Driving Rain Angle (U_T/U_r)	Coefficient of Variation*
		Front	Rear				
1	I	0	0	0.25	0.91	0.18	0.000
2	II	40	40	0.25	0.91	0.18	0.334
3	III	40	80	0.25	0.91	0.18	0.331
4	IV	80	40	0.25	0.91	0.18	0.611
5	V	80	80	0.25	0.91	0.18	0.725
6	I	0	0	0.5	2.00	0.40	0.000
7	II	40	40	0.5	2.00	0.40	0.101
8	III	40	80	0.5	2.00	0.40	0.149
9	IV	80	40	0.5	2.00	0.40	0.290
10	V	80	80	0.5	2.00	0.40	0.267
11	I	0	0	1.0	3.85	0.77	0.000
12	II	40	40	1.0	3.85	0.77	0.076
13	III	40	80	1.0	3.85	0.77	0.093
14	IV	80	40	1.0	3.85	0.77	0.133
15	V	80	80	1.0	3.85	0.77	0.111
16	I	0	0	3.0	6.90	1.38	0.000
17	II	40	40	3.0	6.90	1.38	0.072
18	III	40	80	3.0	6.90	1.38	0.094
19	IV	80	40	3.0	6.90	1.38	0.103
20	V	80	80	3.0	6.90	1.38	0.095

Inflow wind velocity, U_r , is 5 m/s for all scenarios.

Distance between buildings is 40 m for all scenarios.

*Defined as the ratio of the standard deviation to the average of each scenario.

transport and dispersion due to turbulence, ensembles of 200 samples are employed to evaluate various raindrop trajectory statistics for the Type II street canopy. Figure 5 depicts the raindrop trajectory statistics for four different sizes of raindrops ($d_p = 0.25, 0.50, 1$ and 3 mm) released at a fixed height of 240 m. The mean raindrop trajectories are shown by the solid lines and the standard deviations are plotted by the dash lines. It is observed from Figure 5 that trajectories of smaller raindrops are affected more by turbulent fluctuation, resulting in larger standard deviations of trajectories.

Mean Trajectories of Wind Driven Rains

The simulated wind flow patterns mentioned above provide a basic understanding of the complex multi-building perturbed flow field, such as the curved streamlines, sharp pressure gradients, anisotropic turbulence dispersion, flow reattachment, cavity circulation, and flow separation. Consequently, one can expect that the wind driven rainfall variations should

be apparent due to the complex wind velocity fields as shown in Figure 4. Twenty numerical scenario simulations, summarized in Table 1, have been carried out to investigate the effects of building configurations and raindrop size on wind driven rainfall distribution. The first type of street canopy represents the reference case without the effect of a locally building perturbed wind field, resulting in a spatially uniform rainfall distribution. Approximately 1,000 raindrops are released and simulated for each flow type and driving rain angle. Drops are released at a fixed height of 240 m. Initial horizontal positions are varied over a horizontal range such that all of the released raindrops can impinge on the study area. The initial horizontal velocity of individual raindrops is set to be the wind velocity, whereas the initial vertical is set at the terminal fall velocity.

The simulated mean raindrop trajectories around the street canopies with driving rain angles $0.18, 0.40, 0.77$, and 1.38 are displayed in Figures 6 to 9, respectively. It can be seen from these figures that the trajectories of smaller raindrops are more slanting and more influenced by the complex multi building

Figure 4. Simulated Wind Velocity Fields Around Street Canopies for (a) Type I, (b) Type II, (c) Type III, (d) Type IV, and (e) Type V Street Canopy.

perturbed flow field. By contrast, the trajectories of larger raindrops are less affected by their surrounding flow fields and are only slightly deviated by wind, resulting in parallel movement to the building surface. It can be also seen that the impingement of

raindrops on the building envelope increases from the bottom to the top of the building, since raindrops still maintain much of their initial vertical and horizontal momentum. But at lower height, raindrops are moving more slowly in the streamwise direction because

Figure 4 (cont'd). Simulated Wind Velocity Fields Around Street Canopies for (a) Type I, (b) Type II, (c) Type III, (d) Type IV, and (e) Type V Street Canopy.

of both the shape of the power law wind profile and the disturbance of the building perturbed flow field.

Distributions of Wind Driven Rainfalls

Based on the simulated mean trajectories of wind driven raindrops, the microscale redistribution of wind driven rainfalls around street canopies can be analyzed from their terminating positions on the building envelope or ground surface. To assess the redistribution of wind driven rainfalls from the viewpoint of urban drainage design, each street canopy is divided into five horizontal target zones of equal lengths of 40 m – the upwind zone, the front roof zone, the street canyon zone, the rear roof zone, and the downwind zone (Figure 3). These zones cover all of the ground, the façades, and the roofs in the street canopy. As demonstrated in the previous section, a raindrop in street canopies is either directly hitting the ground or impinging onto the building envelope.

Rainwater directly hitting the ground of each zone is treated as direct surface runoff. Rainwater impinging onto the building envelope can be completely absorbed by the building surface or drained off along the building surface to the ground or bounced off the building surface to the ground. The amount of rainwater absorbed or draining down or bouncing off depends on the surface material. Modern buildings are often clad in impervious materials that keep rainwater on the surface, where it can be bounced off or drained off the building surface to the ground. The present study considers the worst case from the viewpoint of drainage system design, which neglects rainwater absorption on the building surface. Consequently, all raindrop impingement can be assumed to contribute immediately to surface runoff. Using the raindrop counting methodology, rainwater terminating on the windward wall of the front building, on the leeward wall of the front building or on the windward wall of the rear building, and on the leeward wall of the rear building should accumulate in the upwind zone, the street canyon zone, and the downwind zone, respectively.

Figure 5. The Raindrop Trajectory Statistics for Type II Street Canopy,
 (a) $d_p = 0.25$ mm, (b) $d_p = 0.50$ mm, (c) $d_p = 1$ mm, (d) $d_p = 3$ mm.

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Figure 6. Simulated Raindrop Trajectories Around Street Canopies With the Driving Rain Angle 0.18.

Figure 7. Simulated Raindrop Trajectories Around Street Canopies With the Driving Rain Angle 0.40.

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Figure 8. Simulated Raindrop Trajectories Around Street Canopies With the Driving Rain Angle 0.77.

Figure 9. Simulated Raindrop Trajectories Around Street Canopies With the Driving Rain Angle 1.38.

In each scenario, the number of the raindrops staying in each zone is normalized by the total number of released raindrops as the rainfall fraction. The coefficient of variation, defined as the ratio of the standard deviation to the average of each scenario, is used to illustrate spatial variation of rainfalls. The simulated results of the rainfall redistributions and the coefficient of variation of the 20 proposed scenarios are summarized in Figure 10 and Table 1, respectively. The simulated results show that distinct rainfall redistributions are found for scenarios with high building configurations and low driving rain angles. The pattern of rainfall impingement for each type of street canopy is also different. For all scenarios with the Type I street canopy, it is observed that raindrops follow curved trajectories and uniformly strike the ground. Wind driven rains distribute on the five target zones uniformly. The coefficient of variation is thus zero. In the scenarios with the Type II street canopy, the raindrops on the five target zones are not uniform, with more rainwater in the upwind zone and less in the downwind zone, due to the blockage effect of the front building and the wind induced recirculation behind the rear building. The rainfall amount in the upwind zone and the downwind zone increases 12 percent to 58 percent and decreases 0 percent to 25 percent, respectively, compared to the Type I street canopy for different driving rain angles.

The Type III street canopy has a tall downstream building configured in such a way that rainwater terminating on the windward face of the rear building is significant, which means more rainfall occurs in the street canyon zone. In comparison with the Type I street canopy, the amount of rainwater in the street canyon zone increases 13 percent to 41 percent for different driving rain angles. For the scenarios with the Type IV and Type V street canopies, due mainly to the blockage effect of the tall building in the front, a large number of raindrops are intercepted on the windward face of the front building, resulting in more rainwater accumulating in the upwind zone and less rainfall being distributed to the rest of the zones. The coefficients of variation are inevitably large, up to 0.725. The rainfall amount in the upwind zone, the street canyon zone, and the downwind zone of the Type V street canopy are 15 percent to 121 percent more, 3 percent to 28 percent less, and 3 percent to 75 percent less, respectively, than those of Type I. As a result, the height of the front building is a significant factor affecting the wind driven rain redistribution. Figure 10 also reveals that the coefficient of variation decreases as the driving rain angle increases for the same street canopy, which implies that the distribution of wind-driven rainfall is less uniform as the wind velocity increases or the raindrop size decreases. However, the coefficient of variation tends to remain

constant as the driving rain angle is greater than 0.77 or the raindrop diameter is greater than 1.0 mm due to significant inertia in the vertical direction.

In summary, the rainfall amount for the upwind zone tends to increase for the five types of street canopies investigated. The increase ranges from 7 percent to 121 percent, depending on the driving rain angles. An overall 0 percent to 75 percent reduction of the rainfall amount in the downwind zone is also observed. The change of the rainfall amount in the front roof zone is similar to that in the rear roof zone, which is reduced by 0 percent to 33 percent. The rainfall in the street canyon zone varies with the building configuration from case to case. The simulated results provide information of microscale redistributions of wind driven rainfalls around the street canopies.

Nonuniform Raindrop Size Distribution

The above section considers a uniform raindrop size distribution such that the rainwater volume in each zone is proportional to the number of raindrops. However, the size distribution of raindrops is actually associated with the intensity of a storm, storm type, and rainfall duration (Mualen and Assouline, 1986; Chang, 1990; Choi, 1999). To simulate realistic rainfalls with nonuniform raindrop size distribution, the simulated results in Figure 10 can be integrated to assess the effect of real raindrop size distributions by simply weighting the volumetric fraction of a range of drop sizes. A sample raindrop size distribution (Table 2) measured at the main campus of the National Taiwan University in June 1990 (Chang, 1990) is taken for demonstration. This rainfall event was a summer thunderstorm with an intensity of 21 mm/hr. The drop size ranges from 0.25 mm to 3.0 mm. The measured volumetric fraction of the raindrop size distribution is also shown in Table 2. Using the simulated results in Figure 10 with linear interpolation for other drop diameters, the spatial rainfall distributions of the five street canopies studied are obtained and shown in Table 3. The relative differences in each zone between the Type I canopy and the Type II to Type V canopies are also calculated. There is about 10 percent variation in spatial extent for the realistic raindrop size distribution. As shown in Table 3, a consistent increase of the rainfall amount from 5 percent to 17.4 percent is observed in the upwind zone. The decrease of rainfall amount in the front roof zone ranges from 3.65 percent to 11.8 percent. The rainfall variation in the street canyon zone is increased by 13.5 percent for the Type III canopy.

It must be noted that this paper focuses on the microscale redistribution of wind driven rainfall in

Figure 10. Simulated Rainfall Distributions of the Street Canopy Scenarios With the Driving Rain Angle (a) 0.18, (b) 0.40, (c) 0.77, and (d) 1.38.

two-dimensional (long) street canopies. A two-dimensional street canopy is only a simplified version of the realistic three-dimensional patterns of street buildings and other urban structures. The length of a two-dimensional street canopy should be at least 5 to 10 times its building height, depending on the building's geometry and arrangement (Theurer, 1999; Kastner-Klein and Plate, 1999). Airflow passing through a two-dimensional street canopy is restricted to transport upward over the roof, and thus a stable vortex perpendicular to the street canyon is observed, whereas wind driven raindrops are free to flow upward over the roof or to flow around the corners of a three-dimensional (short) street canopy. Three-dimensional interaction of corner and cavity vortex near building edges may be formed. Hence, future modeling efforts should consider the distribution of wind driven rainfall around three-dimensional street canopies.

TABLE 2. Raindrop Size Distribution Measured at the Main Campus of the National Taiwan University.

Raindrop Diameter, d_p (mm)	Raindrop Number	Number Fraction (percent)	Raindrop Volume* (mm ³)	Volumetric Fraction (percent)
3.50	0	0.00	0.000	0.00
3.25	0	0.00	0.000	0.00
3.00	1	0.81	16.497	4.93
2.75	1	0.81	10.967	3.28
2.50	8	6.44	73.733	22.02
2.25	10	8.06	70.152	20.95
2.00	12	9.68	58.033	17.33
1.75	7	5.65	21.941	6.55
1.50	13	10.48	28.954	8.65
1.25	21	16.94	28.300	8.45
1.00	23	18.55	17.637	5.25
0.75	20	16.13	7.804	2.33
0.50	5	4.03	0.809	0.24
0.25	3	2.42	0.074	0.02
0.00	0	0.00	0.000	0.00
Total	124	100.00	334.90	100.00

*Measured by the image analyzing system.

TABLE 3. Spatial Rainfall Distributions for a Realistic Raindrop Size Distribution.

	Zone 1 (percent)	Zone 2 (percent)	Zone 3 (percent)	Zone 4 (percent)	Zone 5 (percent)
Type I	20.00	20.00	20.00	20.00	20.00
Type II	22.45 (+12.25)	18.56 (-7.20)	19.67 (-1.65)	19.28 (-3.60)	20.04 (+0.20)
Type III	21.00 (+5.00)	19.27 (-3.65)	22.70 (+13.50)	18.05 (-9.75)	18.98 (-5.10)
Type IV	23.48 (+17.40)	17.64 (-11.80)	18.66 (-6.70)	19.19 (-4.05)	21.03 (+5.15)
Type V	23.17 (+15.85)	17.64 (-11.80)	19.22 (-3.90)	19.62 (-1.90)	20.35 (+1.75)

CONCLUSIONS

A numerical methodology has been developed and applied to conduct numerical scenario simulations of wind-driven rain trajectories around urban street canopies by discharging a large number of raindrops into the computational domain. The effects of building configurations and driving rain angles on microscale redistributions of urban rainfall have been quantitatively investigated. The present study has led to the conclusion that the trajectories of smaller raindrops are more slanting and more influenced by the multi-building-perturbed flow field, whereas the trajectories of larger raindrops move vertically and are less affected by their surrounding flow fields. Impingement of raindrops on the building envelope increases with the height of the building. The height of the front building plays an important role in the wind-driven rainfall variation. The amount of rainfall in the zone upwind of a tall building tends to increase 7 percent to 121 percent, depending on the driving rain angle. An overall 0 percent to 75 percent reduction of the rainfall amount in the downwind zone is observed. The redistribution of wind-driven rainfall is more uniform as the wind velocity increases or the raindrop size decreases. Spatial rainfall variation is insignificant if the raindrop size is greater than 1.0 mm. The simulated results are further integrated to assess the effect of realistic raindrop size distributions by weighting the volumetric fraction of a range of drop sizes. The relative differences in each zone between the Type I canopy and the Type II to Type V canopies are calculated. There is about 10 percent variation in spatial extent for real raindrop size distribution. It is hoped that the results of the present study can contribute to the detailed design of storm water drainage systems in urban areas.

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