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Characterizing Pollutant Plume Dispersion in Urban Atmospheric Surface Layer

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H18-137, TOPIC 5. Urban scale and street canyon modelling: Meteorology and air quality.

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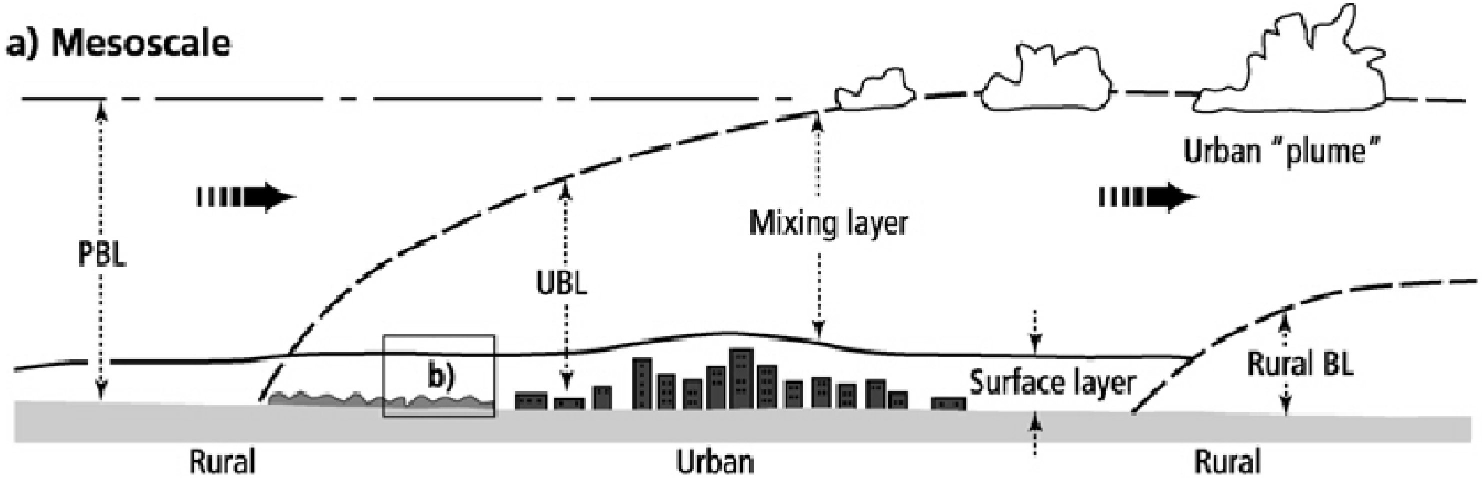
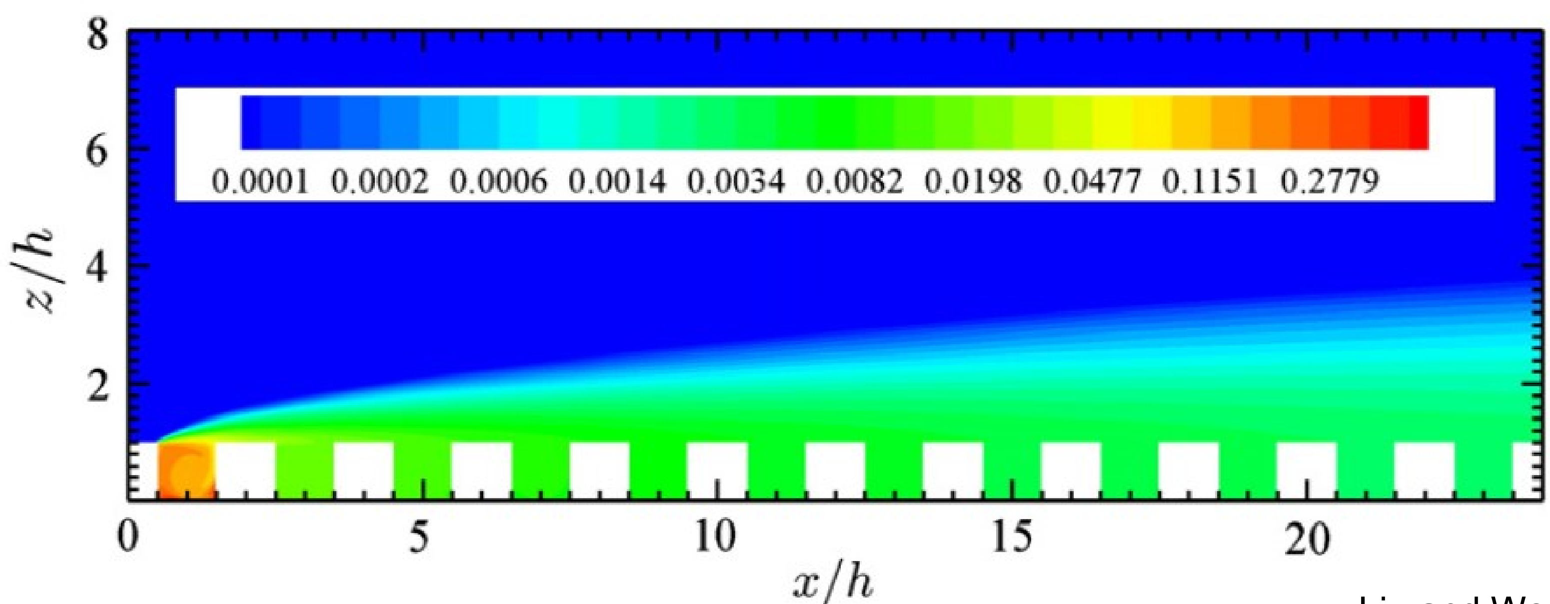
Outline

- Background & objectives
- Theoretical analysis
- Methodology
- Results & discussion

Urban Air Pollution



Piringer et al. (2012)



Liu and Wong (2014)

Background

- Gaussian plume dispersion model

$$c(x,z)=\frac{Q}{\sqrt{2\pi}U\sigma_z}\left\{\exp\left[-\frac{(z-z_c)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+z_c)^2}{2\sigma_z^2}\right]\right\}$$

where c is the mean pollutant concentration, U the mean wind speed in the streamwise direction, z the distances from the ground-level in vertical direction, z_c the emission height, Q the pollutant emission rate and $\boldsymbol{\sigma_z}$ **the vertical dispersion coefficient.**

- Skin-friction coefficient

$$C_f=\frac{\tau_w}{\rho U_\infty^2/2}=2\frac{u_*^2}{U_\infty^2}$$

where τ_w is the shear stress induced by the bottom rough surface, ρ the fluid density, U_∞ the free-stream velocity, u_* the friction velocity estimated using Reynolds stress (Cheng and Castro, 2002; Ploss et al., 2000).

Objective

- To parameterize the vertical dispersion coefficient σ_z in the Gaussian model using skin-friction coefficient C_f

Theory

- Dispersion coefficient, which is a function of atmospheric turbulence, surface roughness & distance from the pollutant source x, can be described by the *K*-theory

$$\sigma_z^2 = 2Kt = 2K\frac{x}{U}$$ where K is the diffusivity & t the pollutant traveling time

- K can be approximated by the friction velocity u_* and mixing length δ, as follows

$$K = u_*\delta$$

- Dispersion coefficient can thus be expressed in terms of u_* & U_m

$$\sigma_z^2 = 2x\delta\frac{u_*}{U} = 2\times x\times\delta\times C_f^{\ 1/2}$$

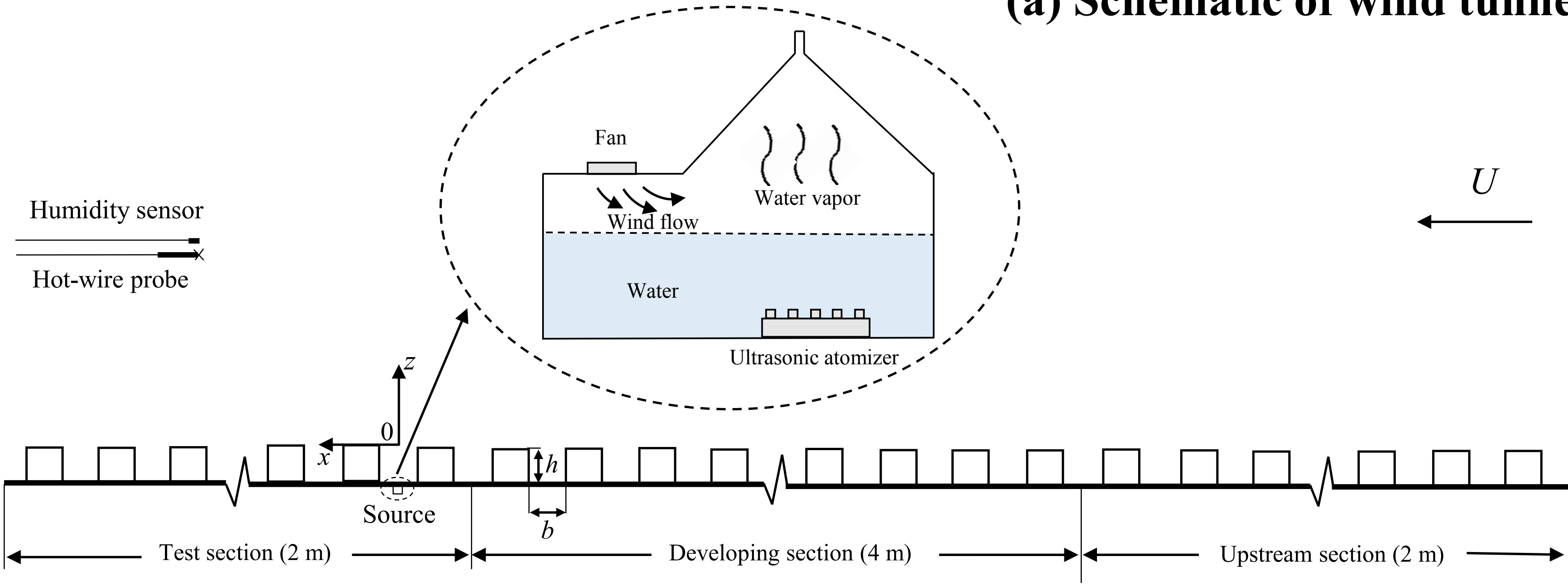
- OR

$$\sigma_z \propto x^{1/2}\times\delta^{1/2}\times C_f^{\ 1/4}$$

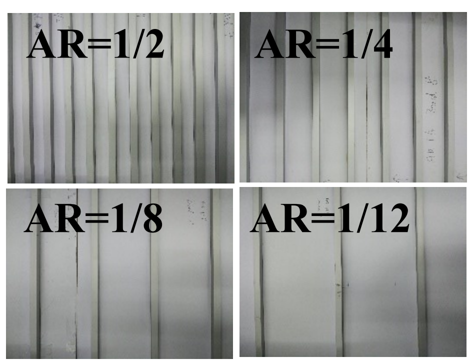
$$\sigma_z/\delta \propto x^{1/2}/\delta^{1/2}\times C_f^{\ 1/4}$$ Dimensionless format

Methodology

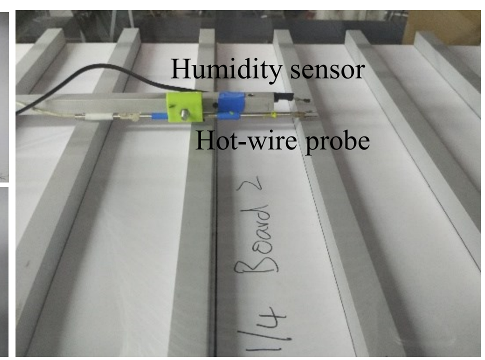
(a) Schematic of wind tunnel



(b) H_2O atomizer



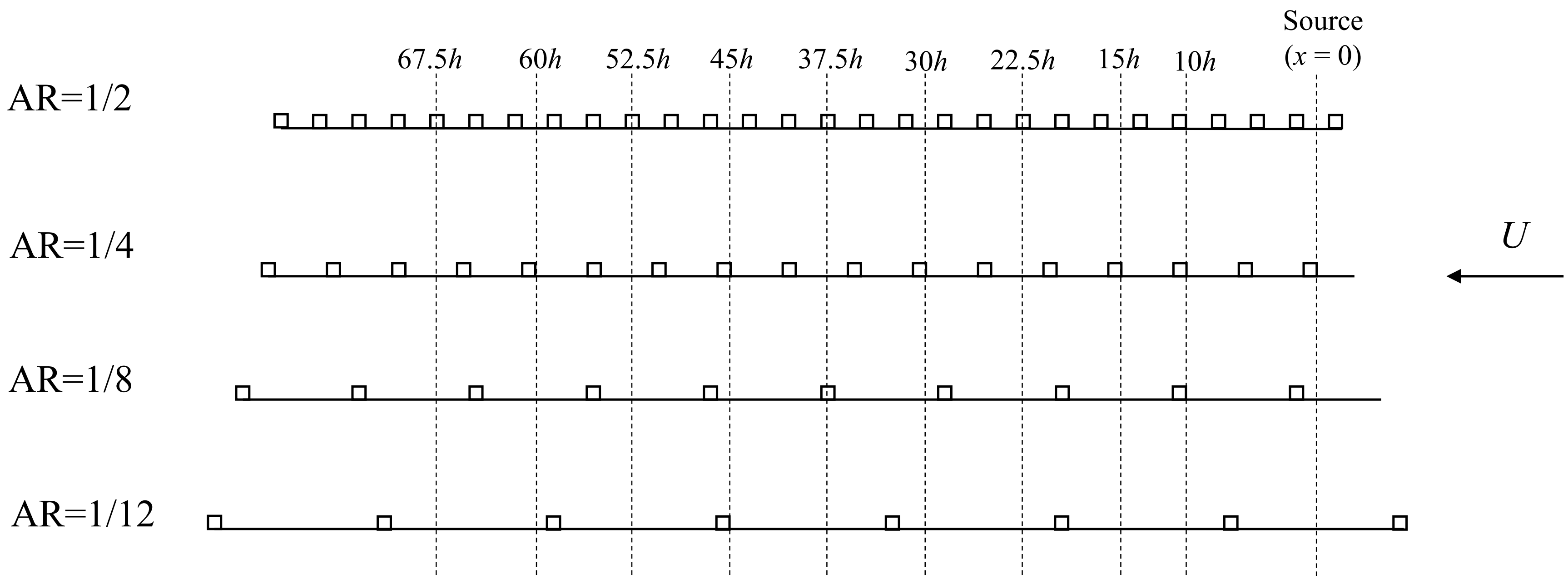
(c) Rib configuration



(d) Sensor location

(e) Source location

Methodology



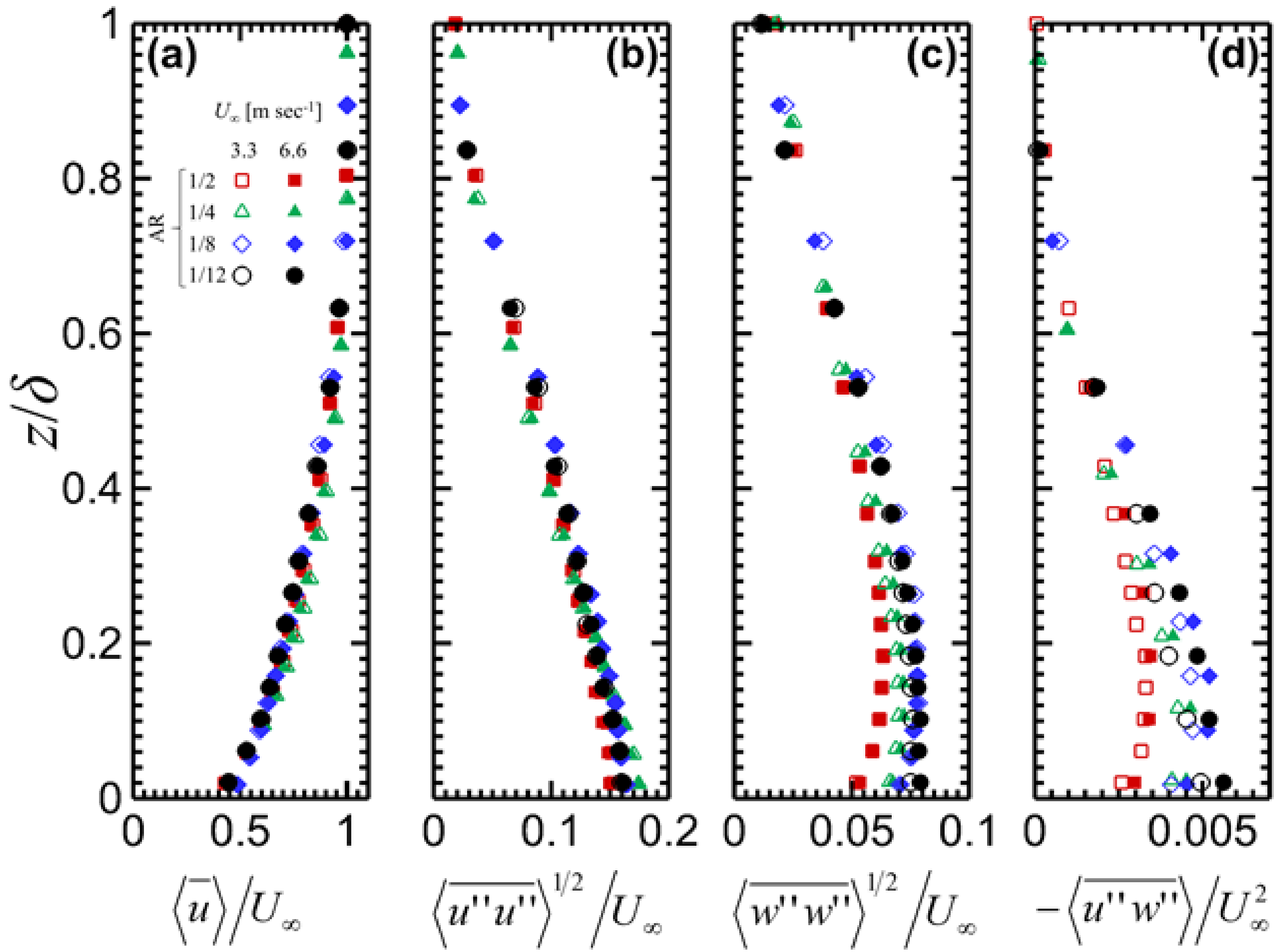
Measurement cases		**Case L1**	**Case L2**	**Case L3**	**Case L4**	**Case H1**	**Case H2**	**Case H3**	**Case H4**
Free-stream	U_∞	3.28	3.31	3.28	3.29	6.66	6.61	6.70	6.60
Rib [mm]	Size h	19	19	19	19	19	19	19	19
	Separation b	38	76	152	228	38	76	152	228
Aspect ratio	AR (= h/b)	1/2	1/4	1/8	1/12	1/2	1/4	1/8	1/12

Note: L denotes lower wind speed measurements, H denotes higher wind speed measurements.

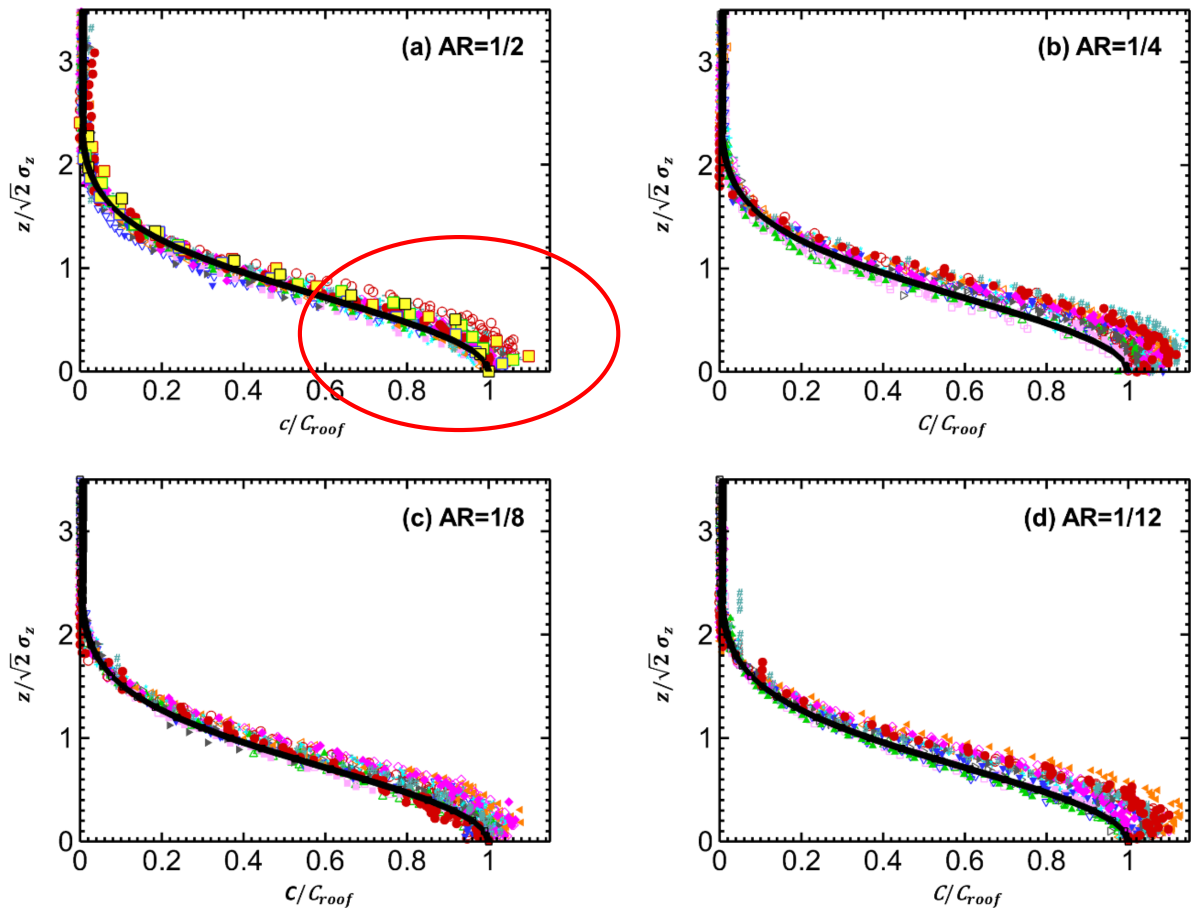
Measurement Parameters

Measurement cases	Low Wind Speed ($U_\infty \approx 3.3$ m sec^{-1})				High Wind Speed ($U_\infty \approx 6.6$ m sec^{-1})			
	Case L1	Case L2	Case L3	Case L4	Case H1	Case H2	Case H3	Case H4
Aspect ratio AR (= h/b)	1/2	1/4	1/8	1/12	1/2	1/4	1/8	1/12
Boundary layer thickness δ [mm]	240	260	285	265	245	265	285	260
Wind speed U_∞ [m sec^{-1}]	3.28	3.31	3.28	3.29	6.66	6.61	6.70	6.60
Friction velocity u_* [m sec^{-1}]	0.184	0.215	0.222	0.224	0.382	0.449	0.474	0.468
C_f (= $2u_*^2/U_\infty^2$) [$\times 10^{-3}$]	7.958	10.351	12.223	11.883	8.352	11.413	12.973	12.835
Re_∞ (= $U_\infty \delta/\nu$)	78,720	86,060	93,385	83,810	163,252	175,165	190,950	168,300
Re_* (= $u_* \delta/\nu$)	4,422	5,597	6,328	5,721	9,356	11,904	13,503	11,938

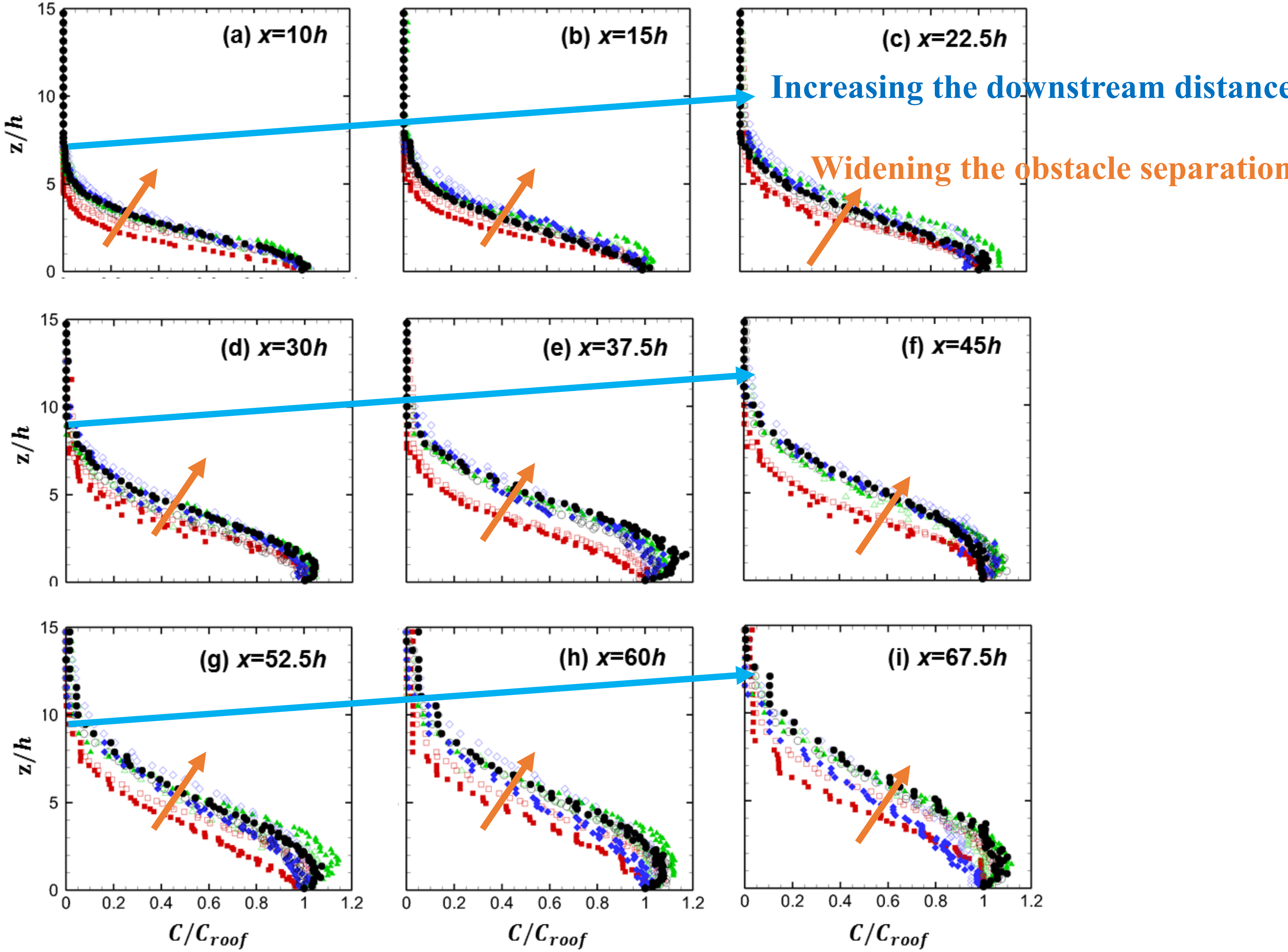
Velocity & Turbulence Profiles



Gaussian distribution



Vertical profiles of dimensionless pollutant concentrations measured over the street canyons with aspect ratios (a) 1/2, (b) 1/4, (c) 1/8, (d) 1/12 at x = 10h (□); 15h (△); 22.5h(▽); 30h (▷); 37.5h (◁); 45h (◇); 52.5h (+); 60h (-); 67.5h (○) at free-stream speed U_∞= 3.3 m/s and x = 10h (■); 15h (▲); 22.5h(▼); 30h (▶); 37.5h (◀); 45h (◆); 52.5h (*); 60h (#); 67.5h (●) at free-stream speed U_∞ = 6.6 m/s. Also shown is the **theoretical Gaussian-form pollutant distributions (*dark solid line*)**. Measurement results at x = 9h (■); 15h (■); 22.5h (■); 30h (■) at free-stream speed U_∞ = 6.8 m/s from Salizzonic et al. (2009).



Vertical profiles of dimensionless concentrations measured at different streamwise locations over street canyons with aspect ratios 1/2 (□) 1/4 (△), 1/8 (◇), and 1/12 (○) at free-stream speed of (a) 3.3 m/s and 1/2 (■) 1/4 (▲), 1/8 (◆), and 1/12 (●) at free-stream speed of (b) 6.6 m/s.

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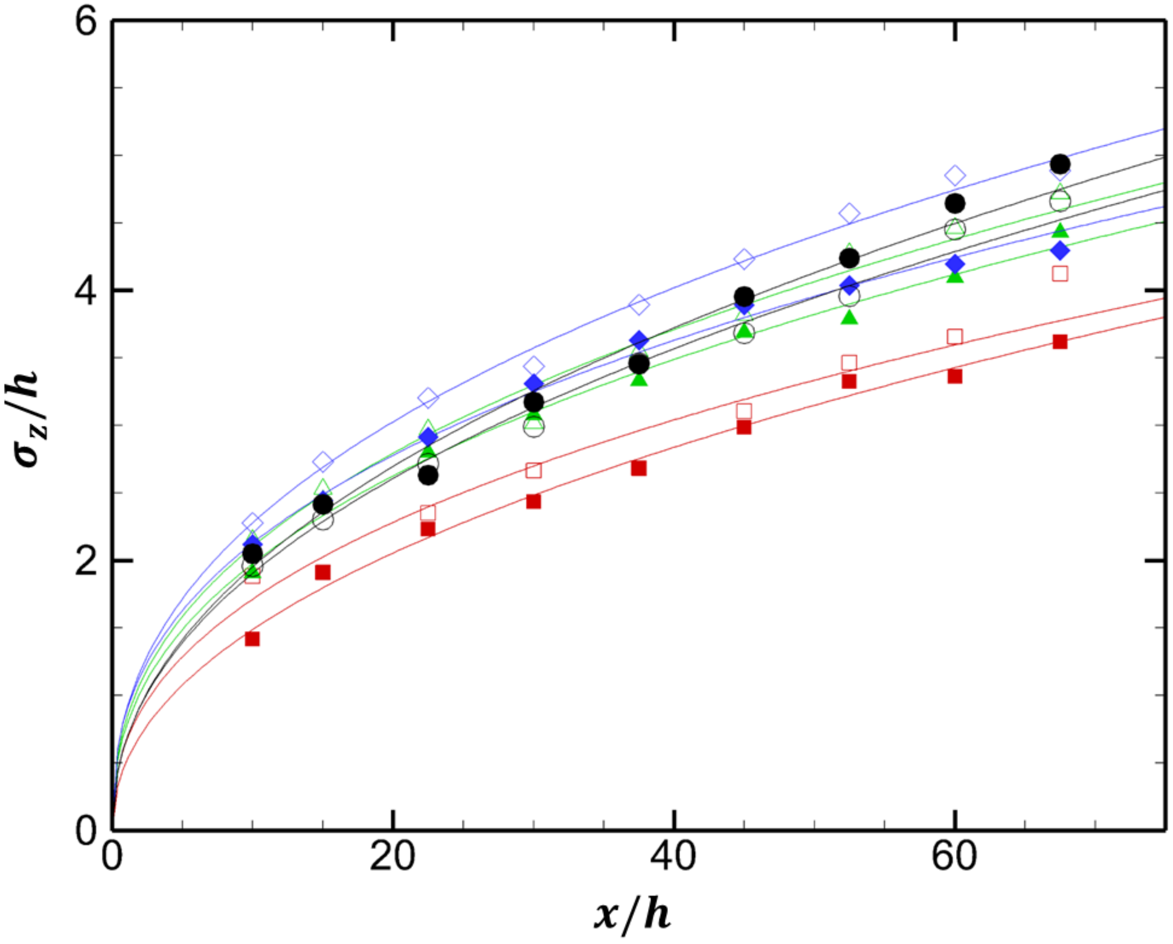
Vertical dispersion coefficient



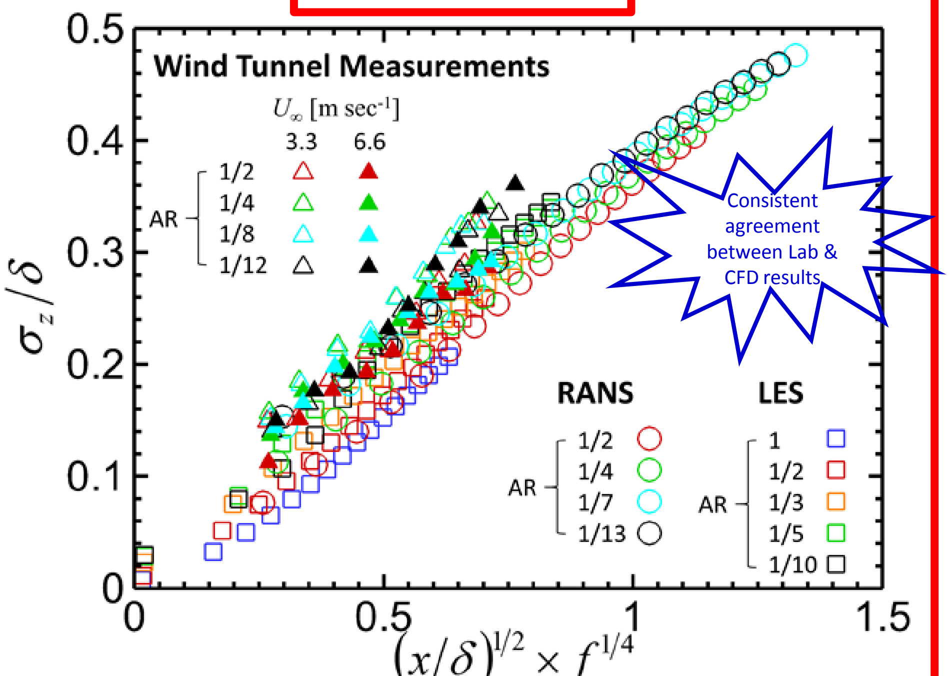
Vertical dispersion coefficients in the streamwise locations over street canyons with aspect ratios 1/2 (□) 1/4 (△), 1/8 (◇), and 1/12 (○) at free-stream speed of (a) 3.3 m/s and 1/2 (■) 1/4 (▲), 1/8 (◆), and 1/12 (●) at free-stream speed of (b) 6.6 m/s.

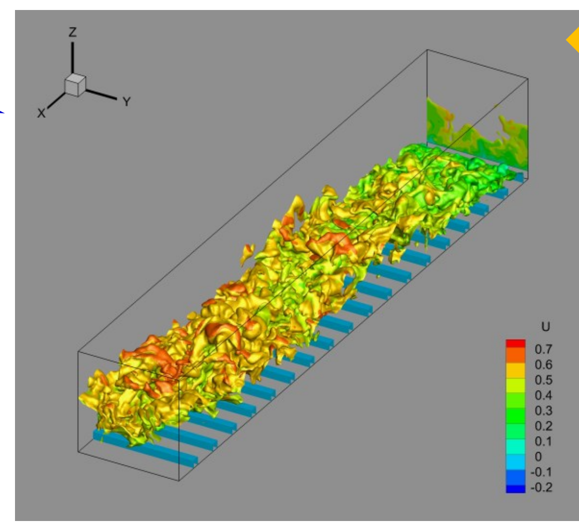
Plume Dispersion over Hypothetical Urban Areas: Computational Model & Laboratory Measurements

Objective

Parameterize the dispersion coefficient σ_z in the Gaussian models using friction coefficient C_f.

Major Findings





Complementary Solution Approach

Impact

Conventionally σ_z is determined based on atmospheric stability that overlooks urban morphology. The results helps excel the functionality of the well-received Gaussian model for urban dispersion.

Summary

- The pollutant concentrations exhibit the conventional Gaussian distributions, suggesting the feasibility of using water vapor as a passive scalar in wind tunnel experiments.

- A strong positive correlation between σ_z & $x^{1/2} \quad \delta^{1/2} \, C_f^{1/4}$ (r^2 = 0.933) is revealed from wind tunnel experiments. The analytical & empirical solutions formulate the basic parameterization of plume dispersion over urban areas.

Acknowledgments

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Thank you very much for your attention
Please feel free to ask questions