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# Multilayer Urban Canopy Modelling and Mapping for Traffic Pollutant Dispersion at High Density Urban Areas

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Photography encouraged

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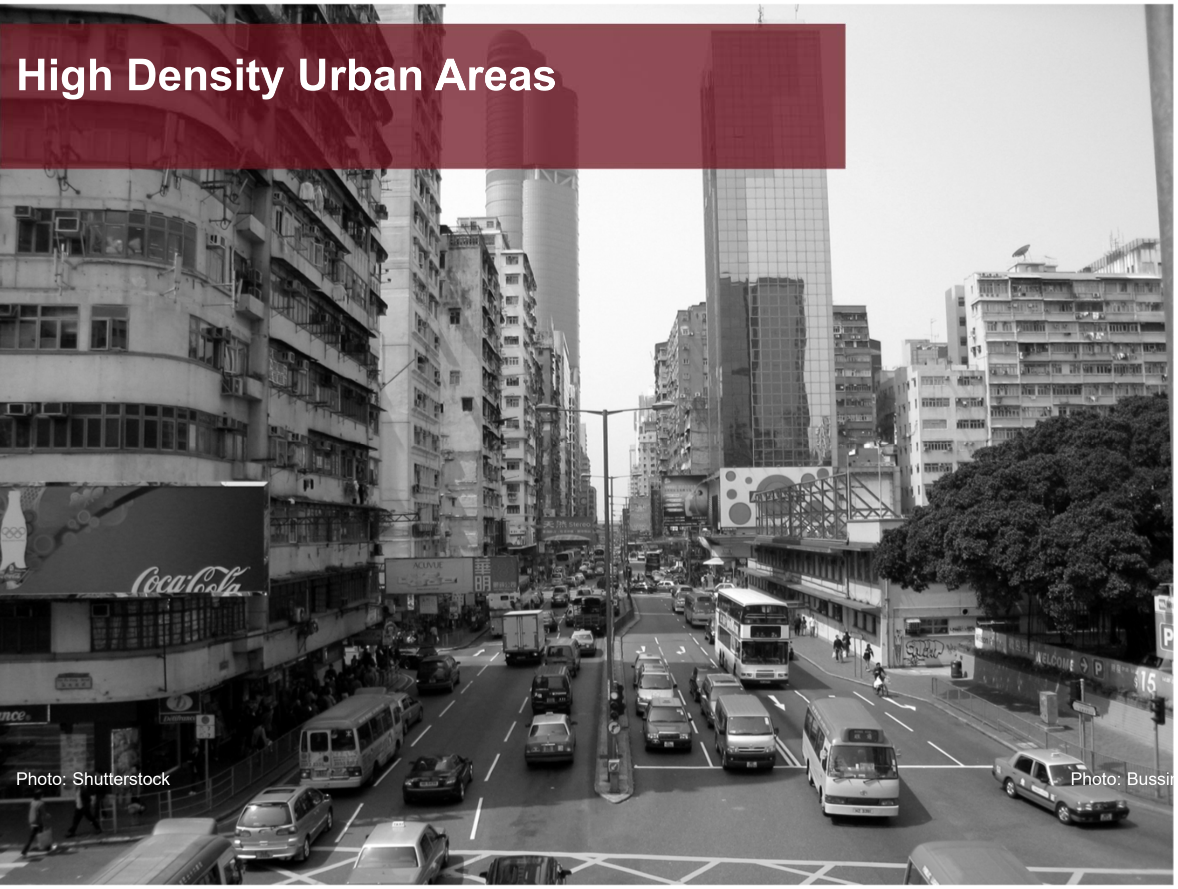
BACKGROUND

## High Density Urban Areas

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Copenhagen: 1,200/km$^2$ (Metro)

Copenhagen: 4,400/km$^2$ (City)

Singapore: 7,804/km$^2$

Hong Kong: 7,400/km$^2$

Hong Kong: 130,000/km$^2$ (City, Mong Kok)

The impact of traffic air pollution on public health at high density urban areas is significant.

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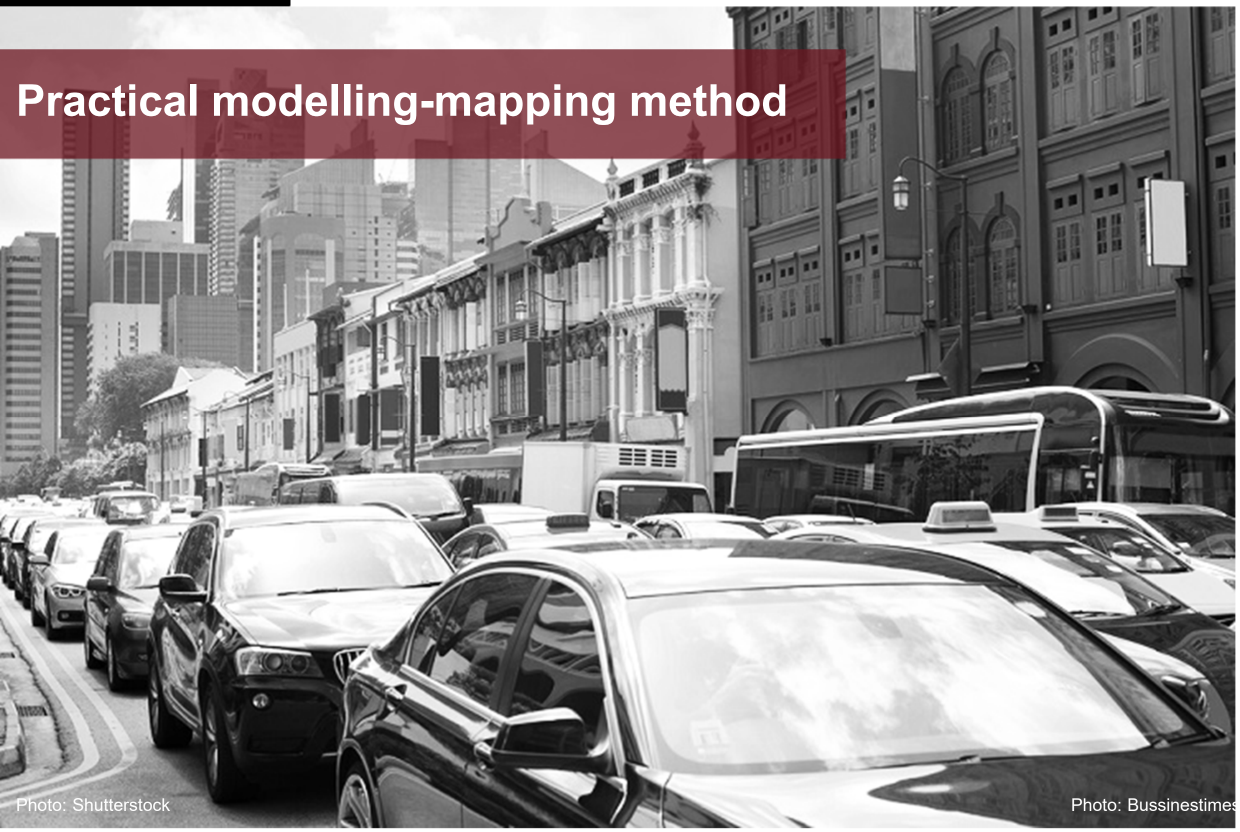
OBJECTIVES

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**Practical modelling-mapping method to support decision-making in urban planning to address air pollution issues.**

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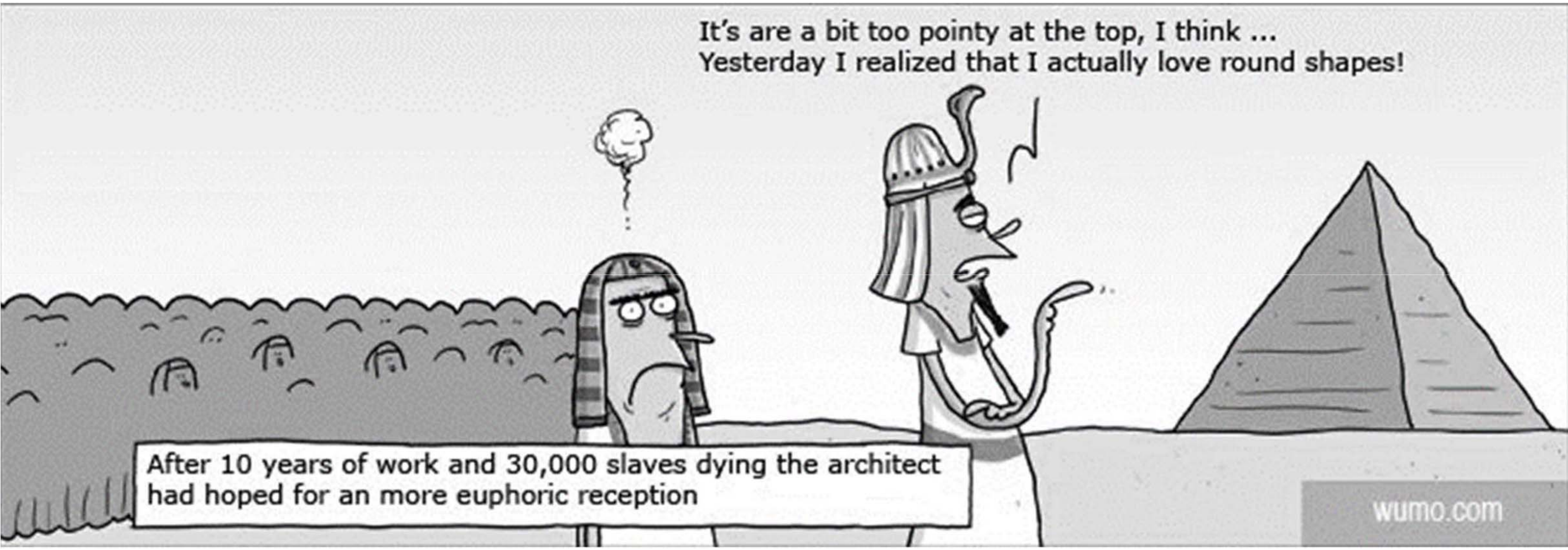


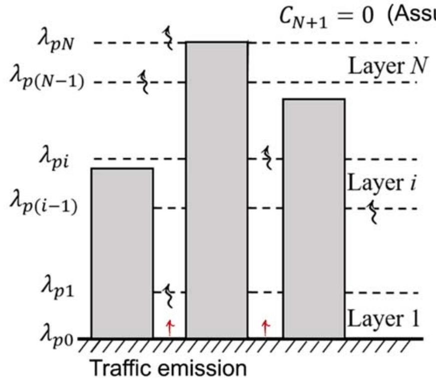
**METHODOLOGY** Mass transfer between urban canopy layers

## Multilayer urban canopy model is developed based on:

- **Exchange velocity estimation**: Layer structure was characterized by canopy drag lengths in the urban canopy layer.
- **Mass conservation**: Box model was applied among sub-layers within street canyons.

## Urban canopy layers and the governing equations per layer

$C_{N+1} = 0$ (Assumption)




$$u_{d(N-1)}(C_{N-1} - C_N)(1 - \lambda_{p(N-1)}) = u_{dN} C_N (1 - \lambda_{pN})$$

$$u_{d(i-1)}(C_{i-1} - C_i)(1 - \lambda_{p(i-1)}) = u_{di}(C_i - C_{i+1})(1 - \lambda_{pi})$$

$$\dot{q}\lambda_e = u_{d1}(C_1 - C_2)(1 - \lambda_{p1})$$

where,

$\boldsymbol{u_d}$ = Mass exchange velocity

$\boldsymbol{\lambda_p}$ = Site coverage ratio

$\boldsymbol{\lambda_f}$ = Frontal area density

$\boldsymbol{C}$ = Pollutant concentration

$\boldsymbol{l}$ = Integral length scale

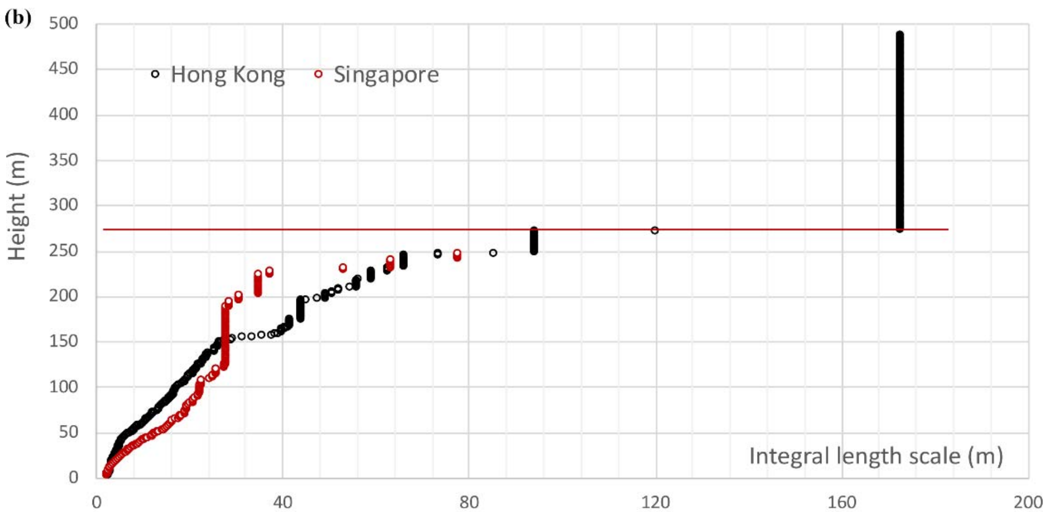
$\boldsymbol{q}$ = traffic-related pollutant emission flux

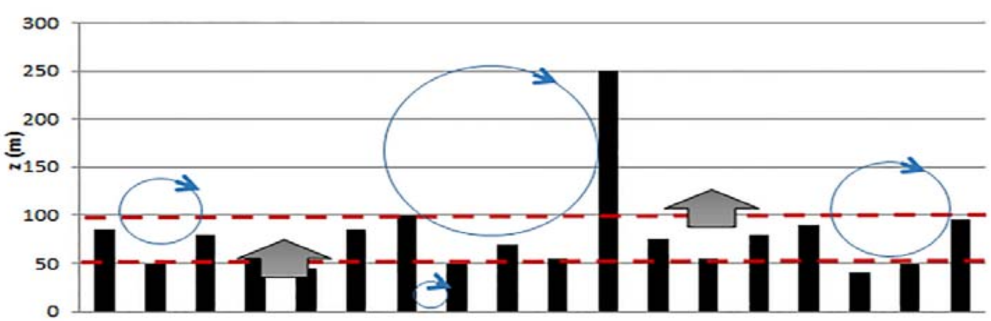
$\boldsymbol{\lambda_e}$ = Ratio of the pollutant emission area to the total lot area

$\boldsymbol{N}$ = Number of layers

METHODOLOGY

## Multilayer urban canopy structure




### Integral length scale of each layer

**Integral length scale (*l*)** at each layer:

$$l = h\frac{(1-\lambda_p)}{\sqrt{2\pi}\sqrt{\lambda_f}}$$

where,

$h$ = The depth of layer

$\lambda_p$ = Site coverage ratio

$\lambda_f$ = Frontal area density

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**METHODOLOGY** Mass transfer between urban canopy layers

## Mass exchange velocity across urban canopy layers

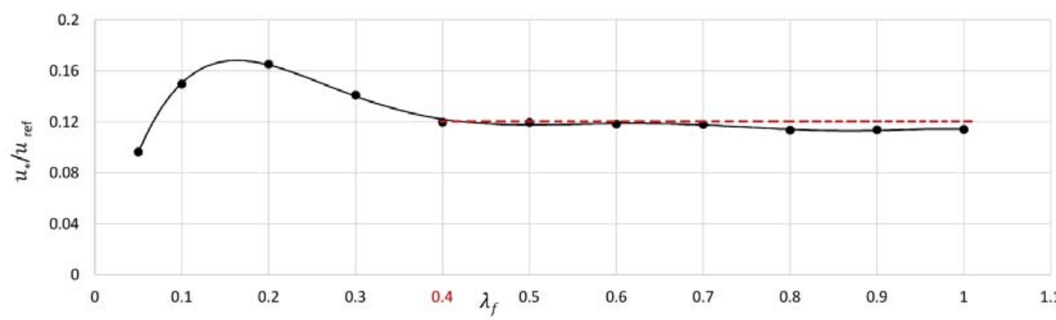
**Friction velocity ($u^*$)** (Yuan et al., 2017):

$$u^* = 0.12 \cdot U_{ref}$$

where,

$u^*$ = Friction velocity

$U_{ref}$ = Mean wind speed at the top of roughness sub-layer $z^*$

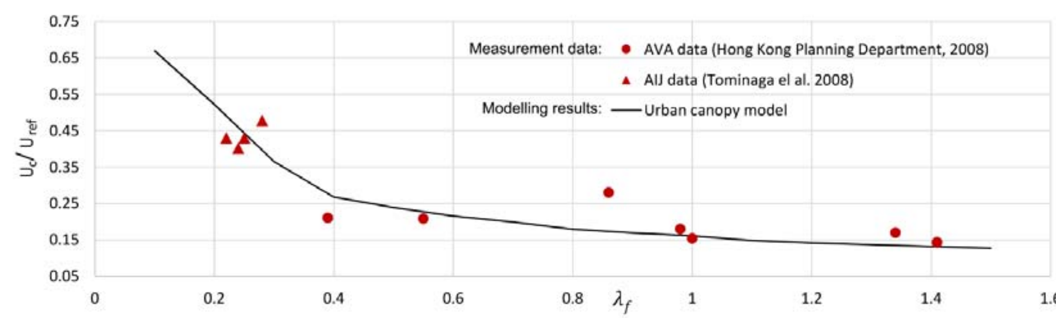



## Validation

**Bentham and Britter model** (Bentham and Britter, 2003):

$$\frac{U_C}{U_{ref}} = \left(\frac{\lambda_f}{2}\right)^{-0.5} \frac{u^*}{U_{ref}}$$

**The new urban canopy model matches the experimental data (AVA data and AIJ data) well, P value = 0.9559**



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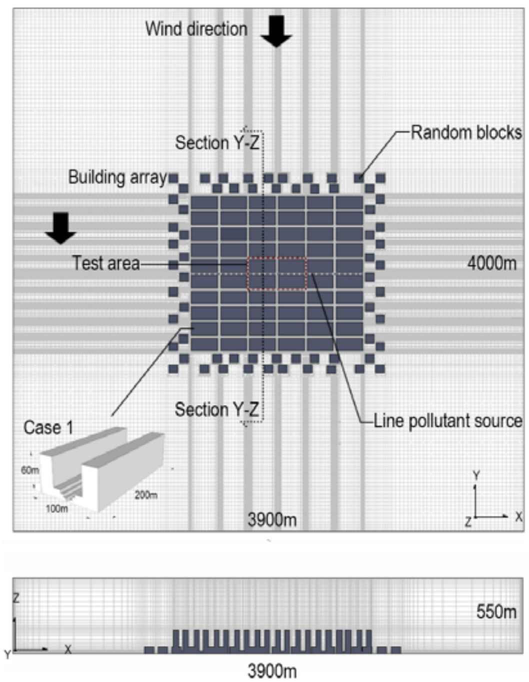
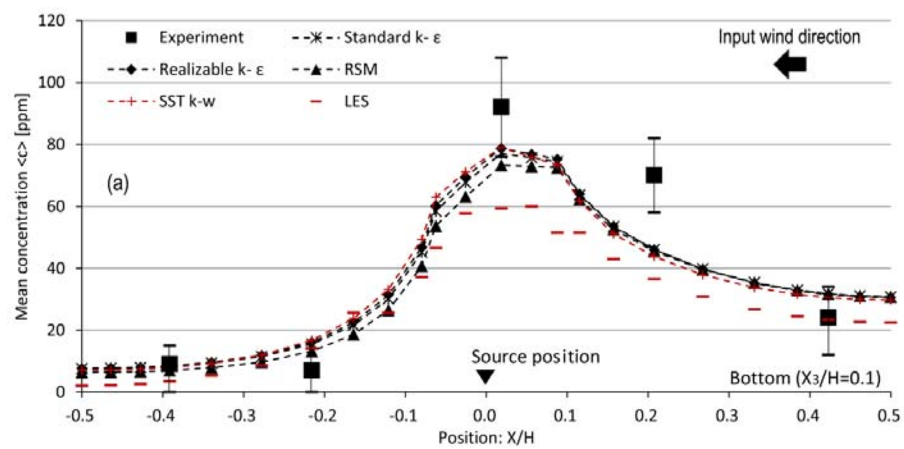
VALIDATION

The present UCM for pollutant dispersion was validated by comparison with **CFD simulations** that were performed in ANSYS Fluent software with the **Shear-Stress Transport (SST) k-ω** turbulence model.

## CFD simulation configurations

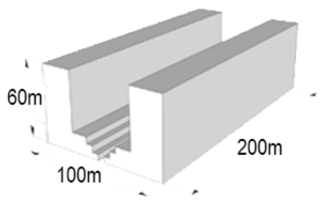



**SST k-ω model** has been validated in previous study **(Yuan et al., 2014)**, in which CFD simulation results were cross-compared with **wind tunnel data** provided by Niigata Institute of Technology **(Tominaga and Stathopoulos, 2011)**.

VALIDATION

## Parametric cases




| | Uniform height | | Non-uniform height | | | | |
|---|---|---|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 |
| Building height 1 (m) | 60 | 90 | 55 | 50 | 45 | 40 | 35 |
| Building height 2 (m) | 60 | 90 | 65 | 70 | 75 | 80 | 85 |

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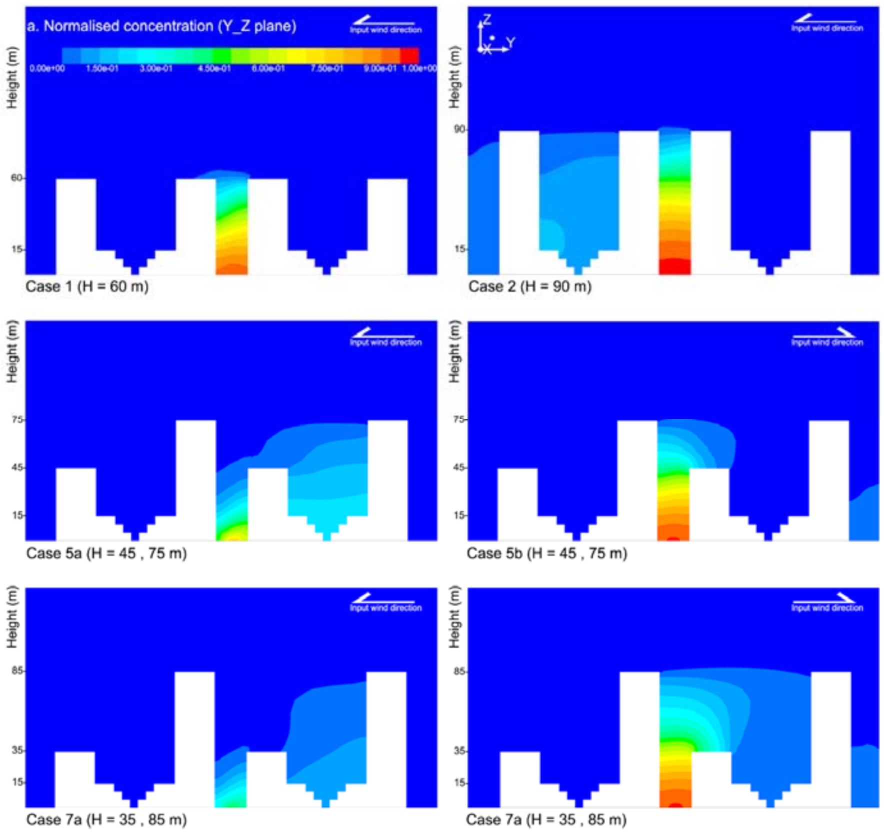
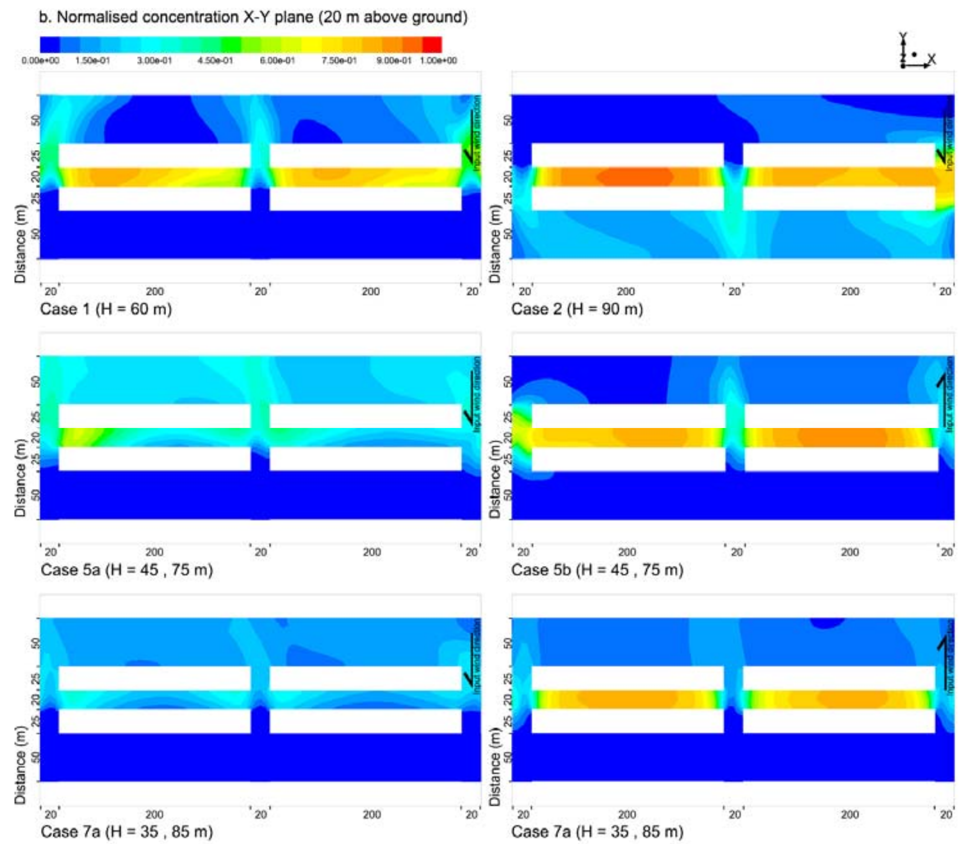
**VALIDATION**

## CFD simulation results



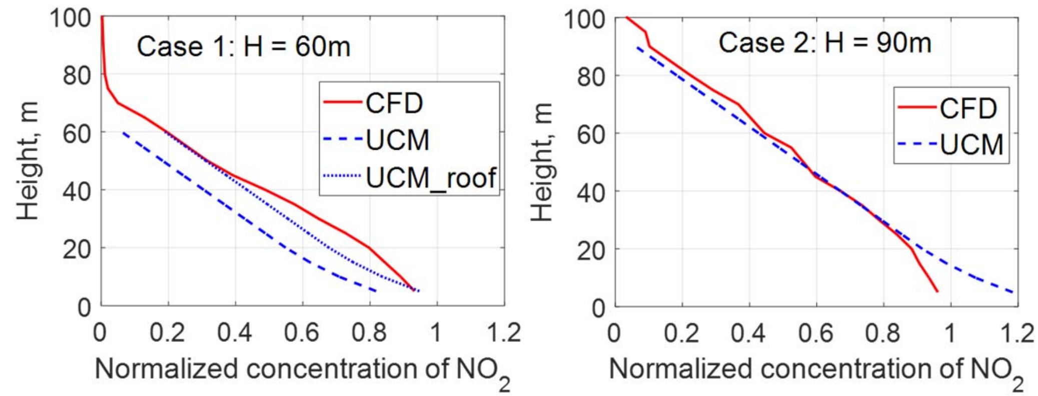



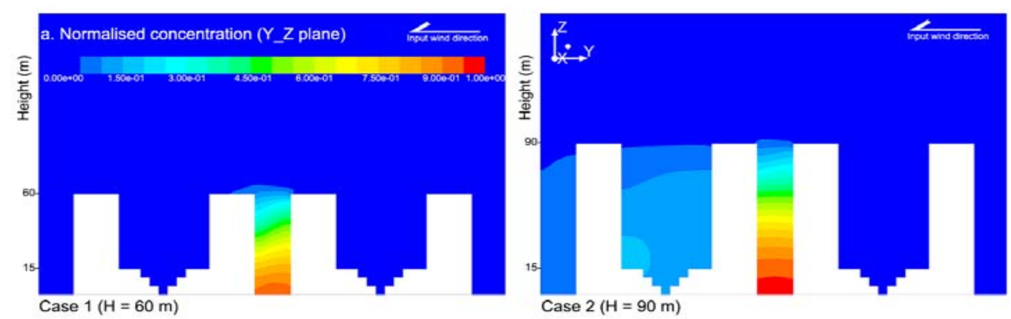
**VALIDATION** Cross-comparison between CFD results and UCM

## Multilayer urban canopy model for buildings with uniform height

With building height of 60m, the concentration of $NO_2$ obtained from UCM is evidently smaller than CFD results, due to assumption in the UCM that there is no pollutant present above building roof.

To include the effect of roof concentration, the UCM is revised through setting the concentration above rooftop as that from the CFD simulation (UCM_roof).



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VALIDATION **Cross-comparison between CFD results and UCM**

## Multilayer urban canopy model for buildings with non-uniform height

With **larger building height variance**, the UCM overestimates the pollutant concentration compared to the CFD simulations, because the current multilayer UCM does not consider horizontal emission advection.

**UCM_adv:**

$$\dot{q}\lambda_e = u_{d1}\,(C_1 - C_2)(1 - \lambda_{p1}) + u_{adv1}\frac{A_c}{A_T}C_1 u_{d(i-1)}(C_{i-1} - C_i)(1 - \lambda_{p(i-1)})$$

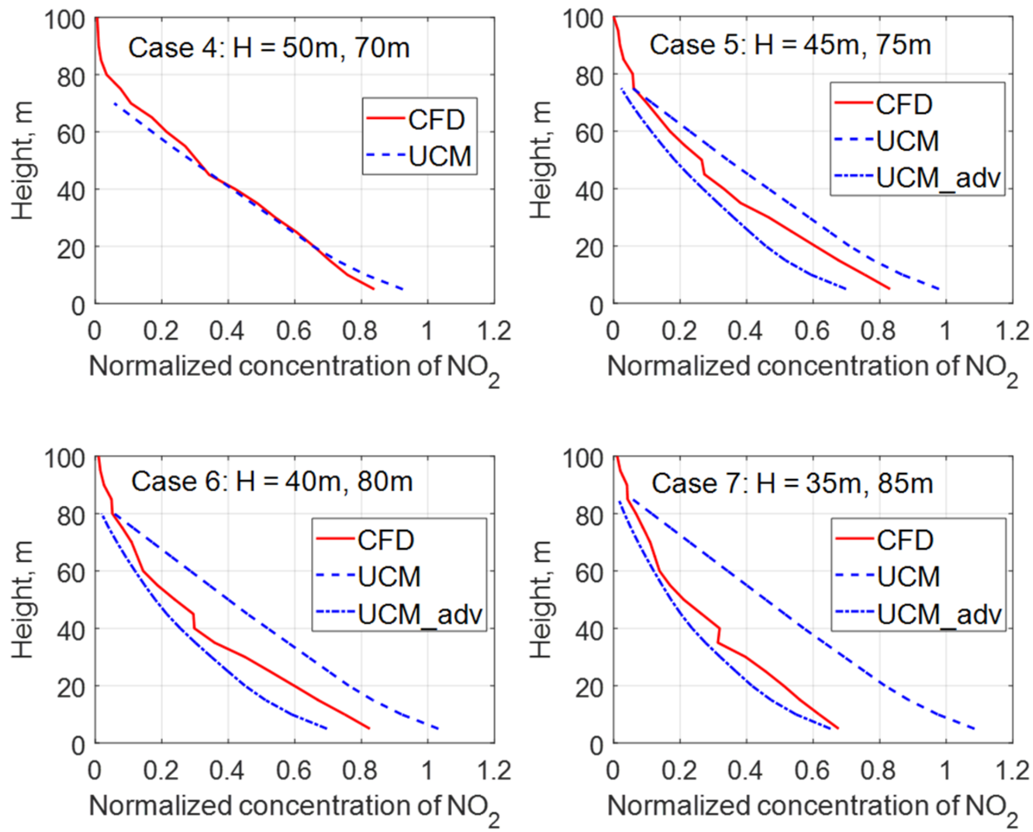
$$= u_{di}(C_i - C_{i+1})(1 - \lambda_{pi}) + u_{advi}\frac{A_c}{A_T}C_i, i = 2,3,\ldots,N$$

where,

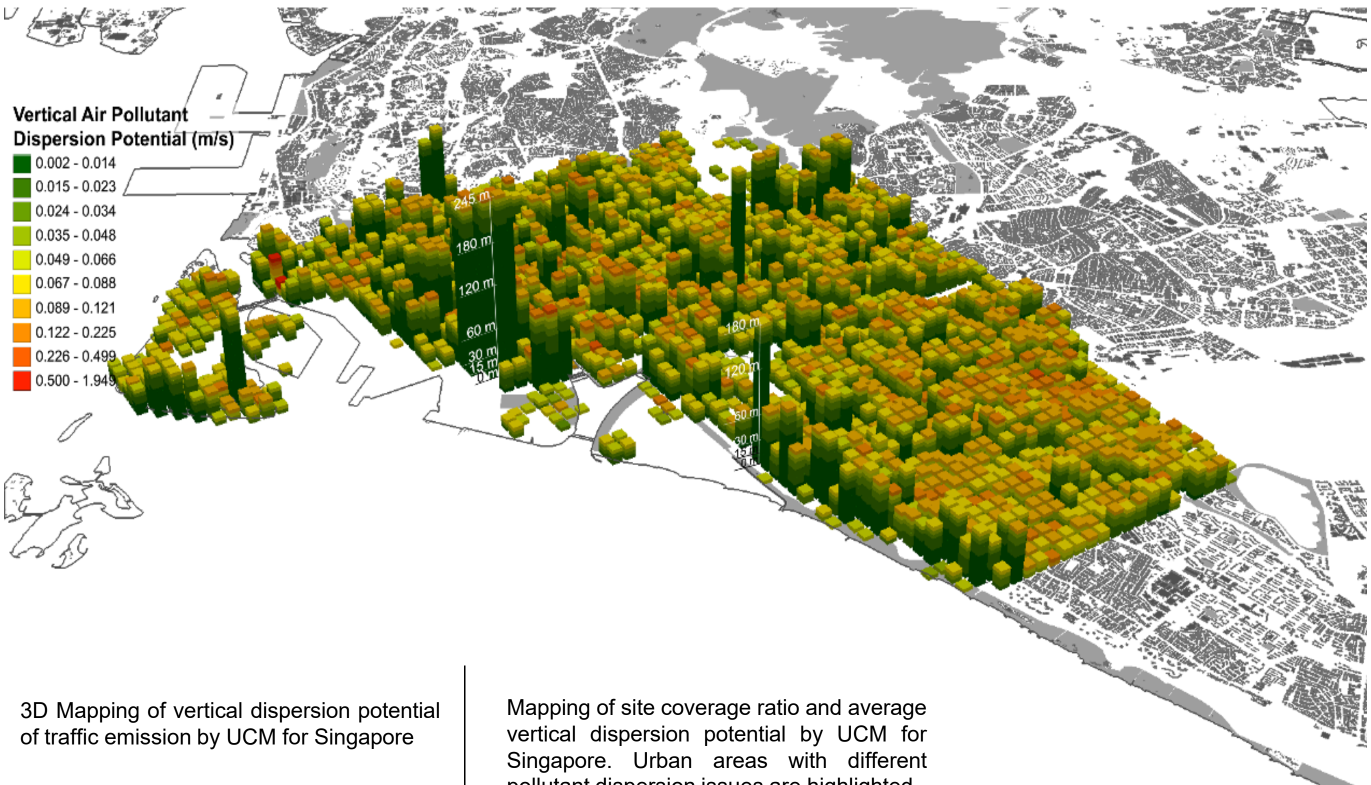
$A_c$ = Cross section of each layer

$A_T$ = Lot area

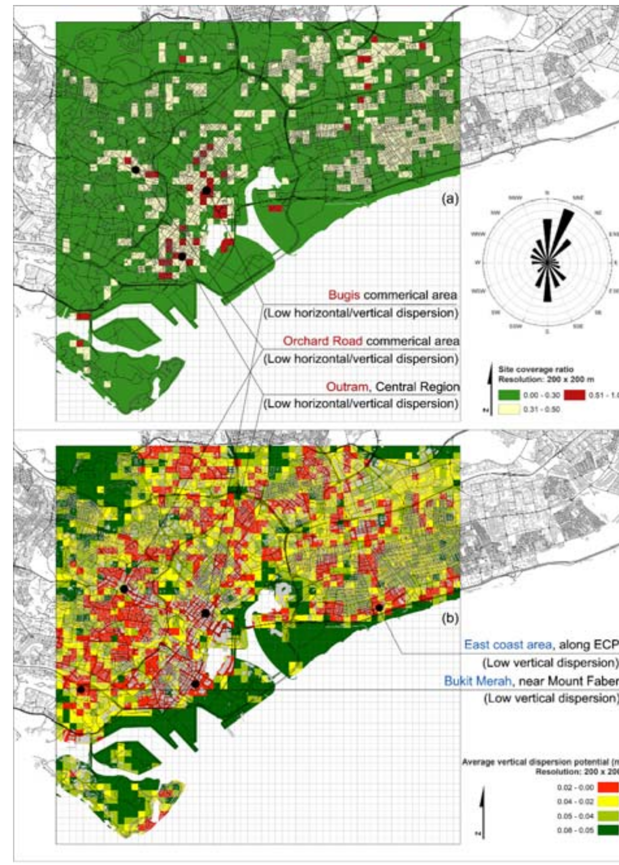
$u_{adv1}$ = Averaged horizontal wind speed in the $i$-th layer



## IMPLEMENTATION




3D Mapping of vertical dispersion potential of traffic emission by UCM for Singapore




Mapping of site coverage ratio and average vertical dispersion potential by UCM for Singapore. Urban areas with different pollutant dispersion issues are highlighted.

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# Multilayer urban canopy modelling and mapping for traffic pollutant dispersion at high density urban areas

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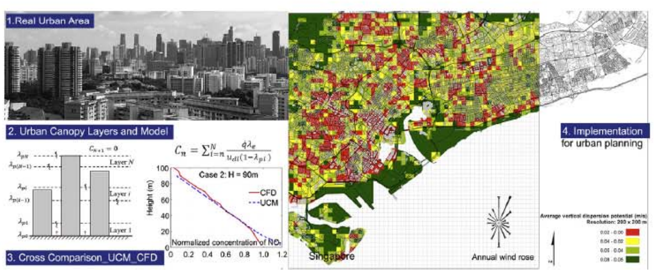
## HIGHLIGHTS

- We create a practical model to estimate vertical pollutant dispersion potential.
- The model is derived based on understandings of mass and momentum conservation.
- Friction velocity, representing momentum flux, is modeled and validated.
- We clarify the effect of heterogeneous urban spatial characteristics on air pollutant dispersion.

## GRAPHICAL ABSTRACT

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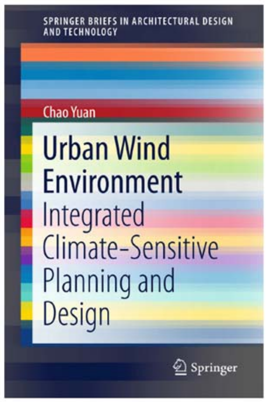


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