The influence of urban heat island circulation in idealized city

-- from building scale to city scale

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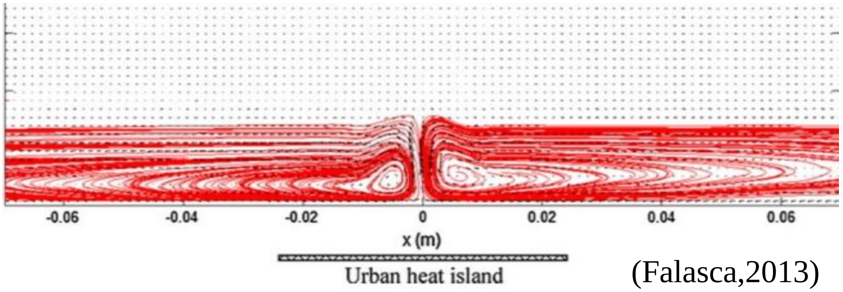
Why do we consider the urban heat island circulation ?

Horizontal temperature gradient → Horizontal pressure gradient → UHIC

Preconditions for urban heat island circulation (UHIC)

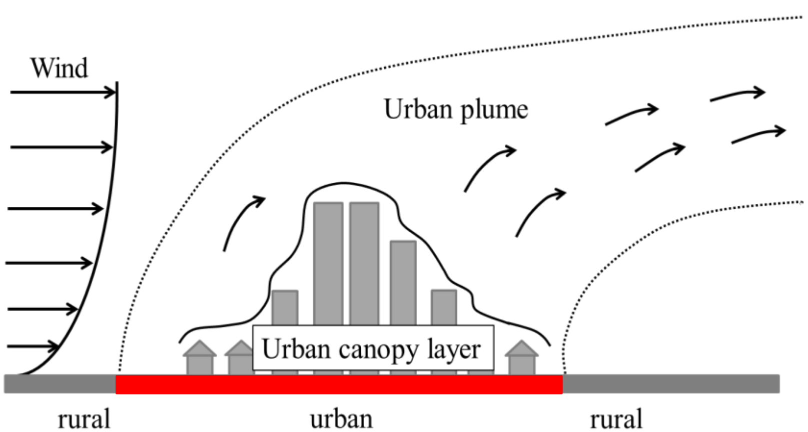
- Thermal inversion layer
- Zero background wind



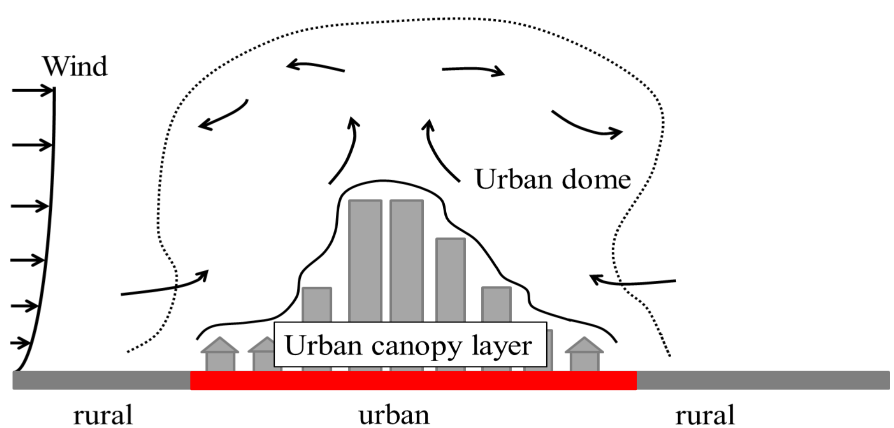
(Falasca,2013)

When UHIC happened, the worse pollution and warmer scenarios generally happened compared with the windy day .

Urban plume model (wind speed > 3 m s^{-1})

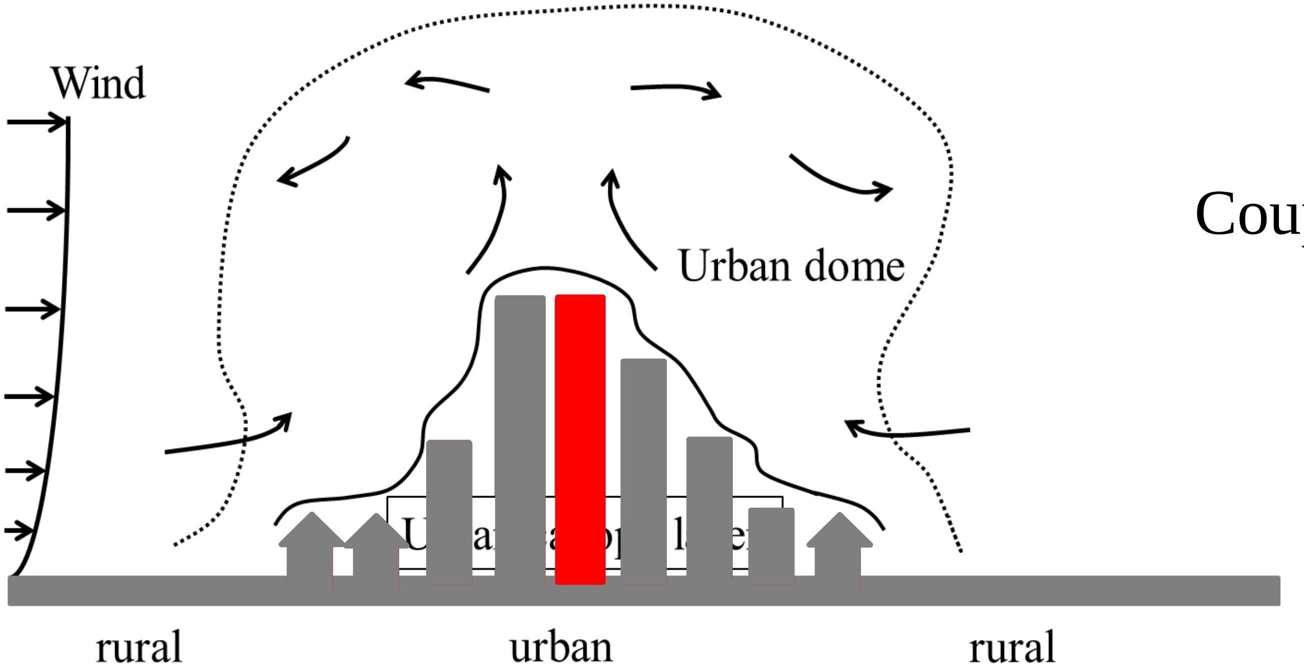


Urban plume model (wind speed < 3 m s^{-1})



Models

Urban plume model (wind speed < 3 m s^{-1})



Coupling method?

It is not easy to anlyze the air flow in the canopy or around a single building by coupling meothd.

The boundary condition changes with time during the UHIC evolution.

CSCFD compared with traditional CFD

Modified CFD model -- City-Scal CFD (CSCFD)

Modeling the mesoscale phenomena

- Coordinate transformation
- Modifying basic equations and turbulence by comparing with mesoscale atmospheric governing equation
  - Coriolis terms
  - Modified buoyancy term
  - Compressibility term for energy equation
  - Coordinate transformed terms

Modeling the overall city scale effect

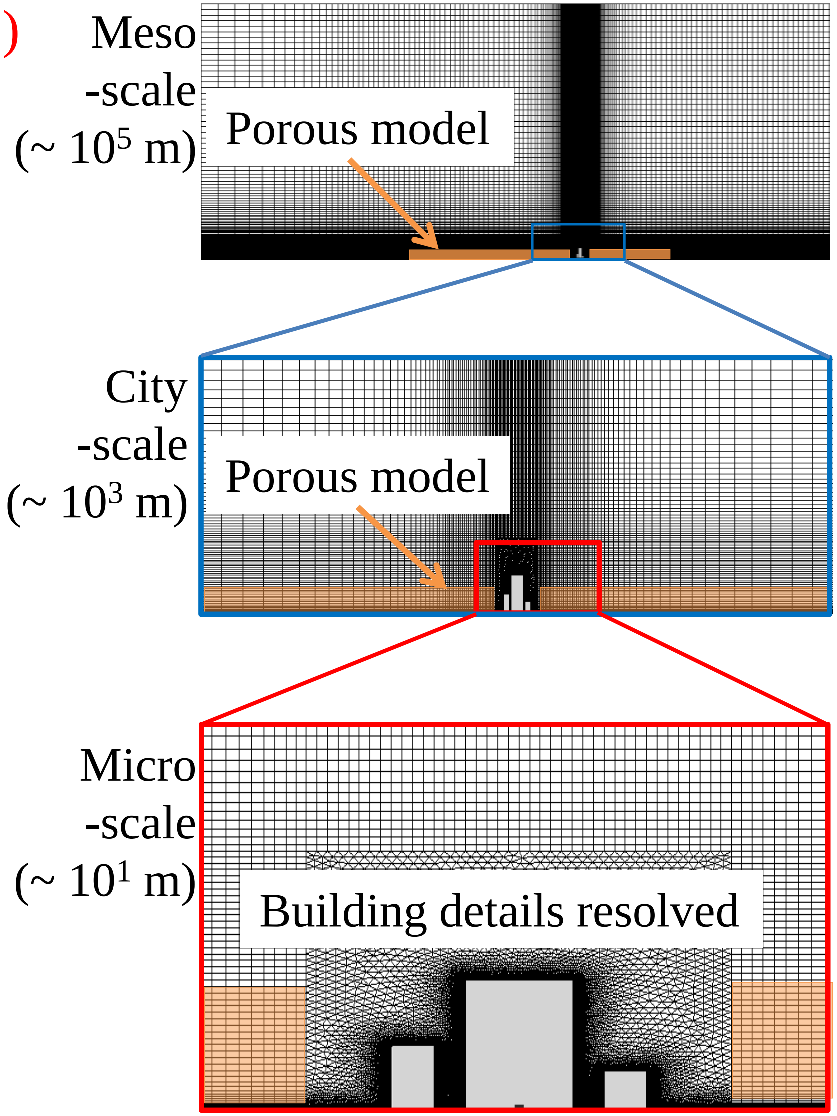
- Adding porous turbulence model

Modeling the 24-hour variation

- Using daily surface temperature for ground

Improving numerical stability

- Using an absorbing layer at the top



CSCFD - basic governing equations

$$\frac{d\left(\rho_0 \phi \overrightarrow{V_n}\right)}{dt} = -\nabla_n \phi p_n + \nabla_n\left(\mu_{\text{eff}} \nabla_n \phi \overrightarrow{V_n}\right) + \boxed{\phi \rho_0 \beta\left(T_n - T_0\right) g + \phi \vec{F}_C + \phi \vec{F}_n + \vec{F}_\phi}$$

$$\frac{d\left(\phi \rho_0 C_{\text{p}} T_{\text{n}}\right)}{dt} = \nabla\left(k_{\text{eff}} \nabla \phi T_n\right) + \boxed{\phi S_T + S_\phi}$$

$$\vec{F}_C = \begin{bmatrix} \rho_0 f v - \rho_0 l w_n J \\ -\rho_0 f u \\ \rho_0 l u J \end{bmatrix}$$

Coriolis terms

$$\vec{F}_n = \begin{bmatrix} 0 \\ 0 \\ \left(J^2 - 1\right)\left(\rho_0 \beta\left(T_n - T_0\right) g + \overrightarrow{F_c}\right) + \zeta \rho_0 w_n{}^2 J - p_n \xi\left(J + 1 + \zeta z_n\right) \end{bmatrix}$$

Coordinate transformed terms

$$\rho_0 \beta\left(T_n - T_0\right) g$$

Modified buoyancy term

$$\vec{F}_\phi = -\phi^2 \frac{\mu_l}{K} \overrightarrow{V_n} - \phi^3 \rho_0 \frac{C_F}{\sqrt{K}} Q^f \overrightarrow{V_n}$$

Porous model terms

$$S_\phi = \rho_0 \frac{(1-\phi)}{\bar{H}} Q_{\text{sen}}$$

Modified heat source considering porosity

$$S_T = J C_p \rho_0 w_n \left(\Gamma_s - \frac{g}{C_p}\right)$$

A transformed compressibility term not existing in the conventional CFD

CSCFD - turbulence governing equations

$$\frac{d}{dt}\left(\phi\rho_0 k_n\right) = \nabla_n\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla_n \phi k_n\right) + \phi G_{k_n} + \phi G_{b_n} - \phi\rho_0\varepsilon_n + \boxed{\phi S_{k_n} + S_{k_\phi}}$$

$$\frac{d}{dt}\left(\phi\rho_0\varepsilon_n\right) = \nabla_n\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla_n \phi\varepsilon_n\right) + \phi C_{1\varepsilon}\frac{\varepsilon_n}{k_n}\left(G_{kn} + C_{3\varepsilon}G_{b_n}\right) - \phi C_{2\varepsilon}\rho_0\frac{\varepsilon_n{}^2}{k_n} + \boxed{\phi S_{\varepsilon_n} + S_{\varepsilon_\phi}}$$

$$S_{k_n} = \beta g\frac{\mu_t}{Pr_t}\left(\Gamma_s - \frac{g}{C_p}\right)$$

$$S_{\varepsilon_n} = C_{1\varepsilon}C_{3\varepsilon}\frac{\varepsilon_n}{k_n}\beta g\frac{\mu_t}{Pr_t}\left(\Gamma_s - \frac{g}{C_p}\right)$$

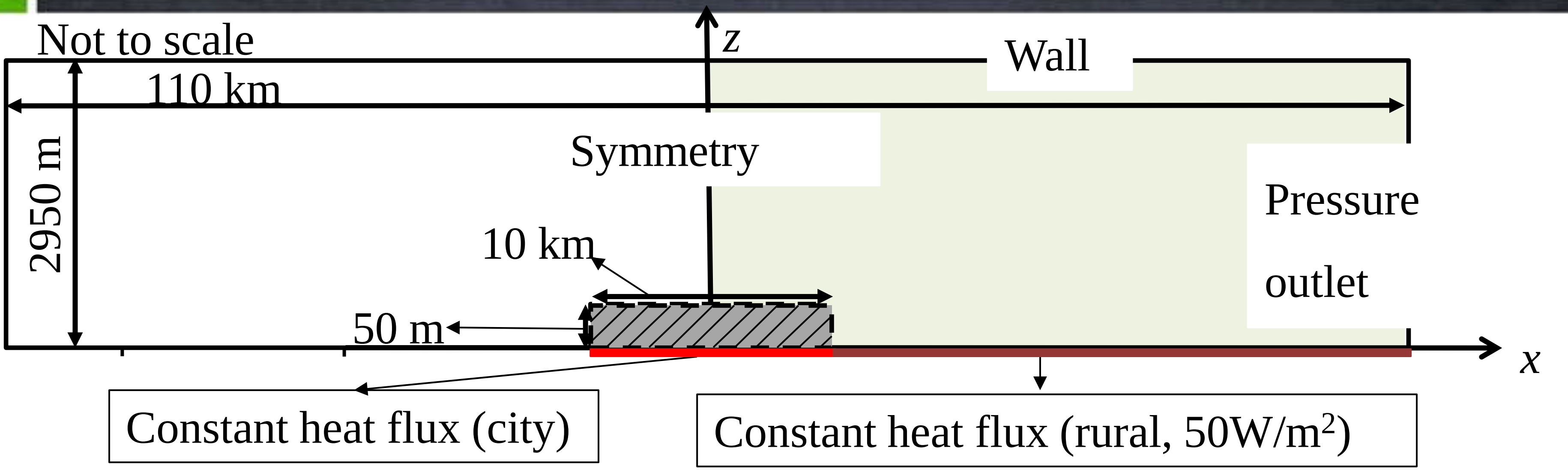
Coordinate transformed terms

$$S_{k\phi} = -\left(2\phi^2\frac{\mu_l}{K}k_n + \frac{8}{3}\phi^3\rho_0\frac{C_F}{\sqrt{K}}Q_n k_n - 2\phi^3\frac{C_F}{\sqrt{K}}F_k\right)$$

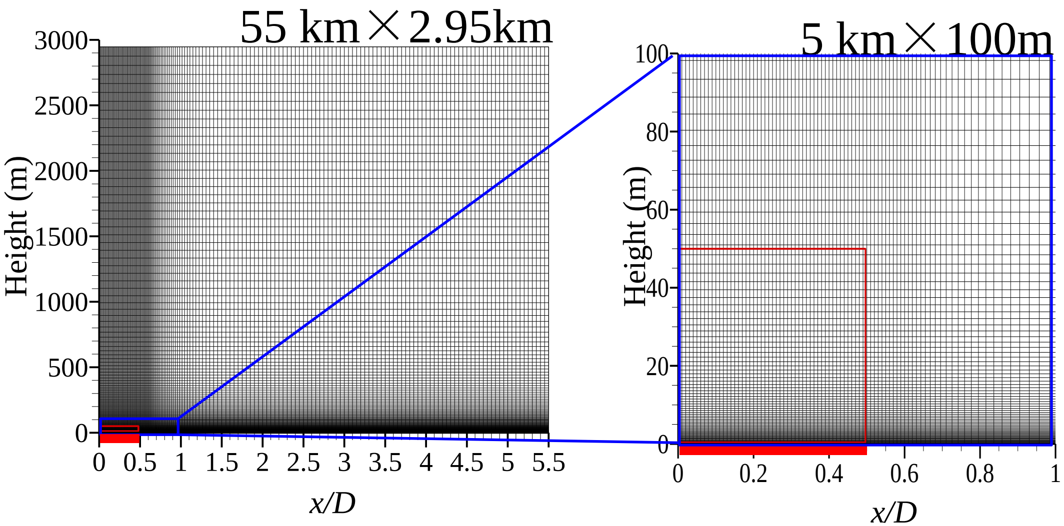
$$S_{\varepsilon\phi} = -\left(2\phi^2\frac{\mu_l}{K}\varepsilon_n + \frac{8}{3}\phi^3\rho_0\frac{C_F}{\sqrt{K}}Q_n\varepsilon_n + \frac{8}{3}\phi^3\frac{C_F}{\sqrt{K}}\frac{\partial k_n}{\partial x_r}\frac{\partial Q^f}{\partial x_r}\right)$$

Porous turbulence model terms

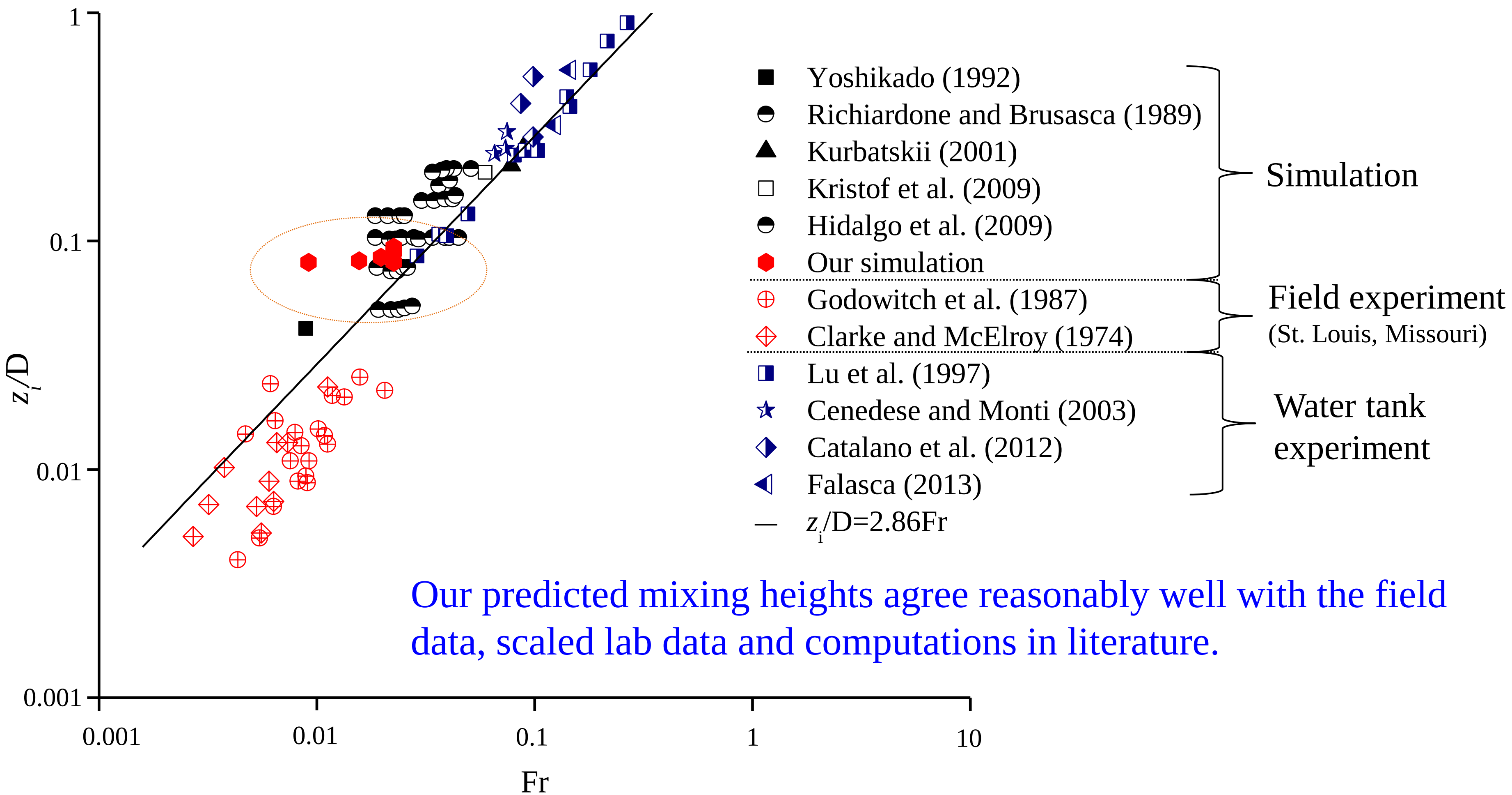
Quasi-steady UHIC – domain



	City area	Other area
Time step	1 second	
Simulation time	10 hours to achieve quasi-steady state	
Porosity	0.75	1.0



Comparing with others' data

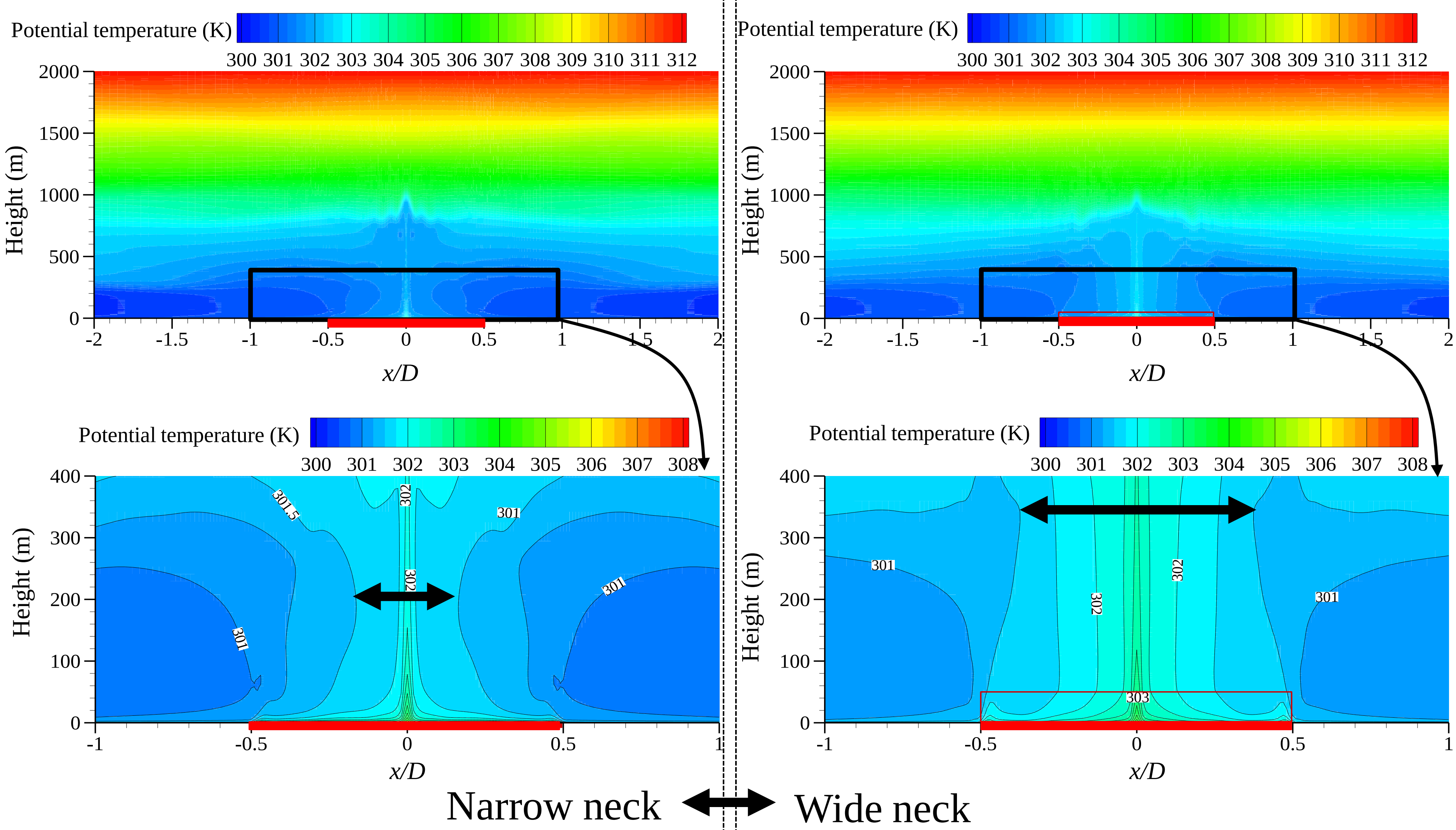


Mixing height(z_i): the height where the maximum difference between the plume centerline and ambient density profiles occurs (Lu and Arya, 1997)

Quasi-steady UHIC– comparing a flat city and a porous city

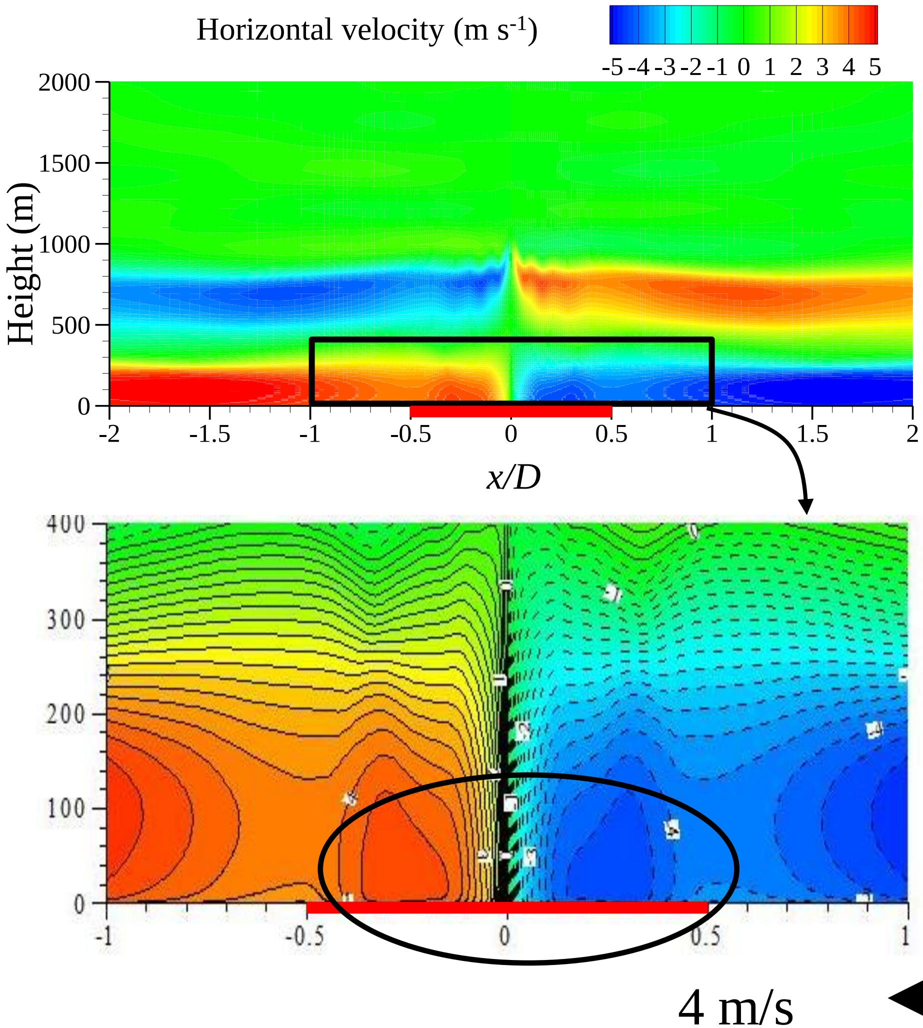
Flat city

Porous city (Porosity= 0.75 $\lambda_p = 0.25$)

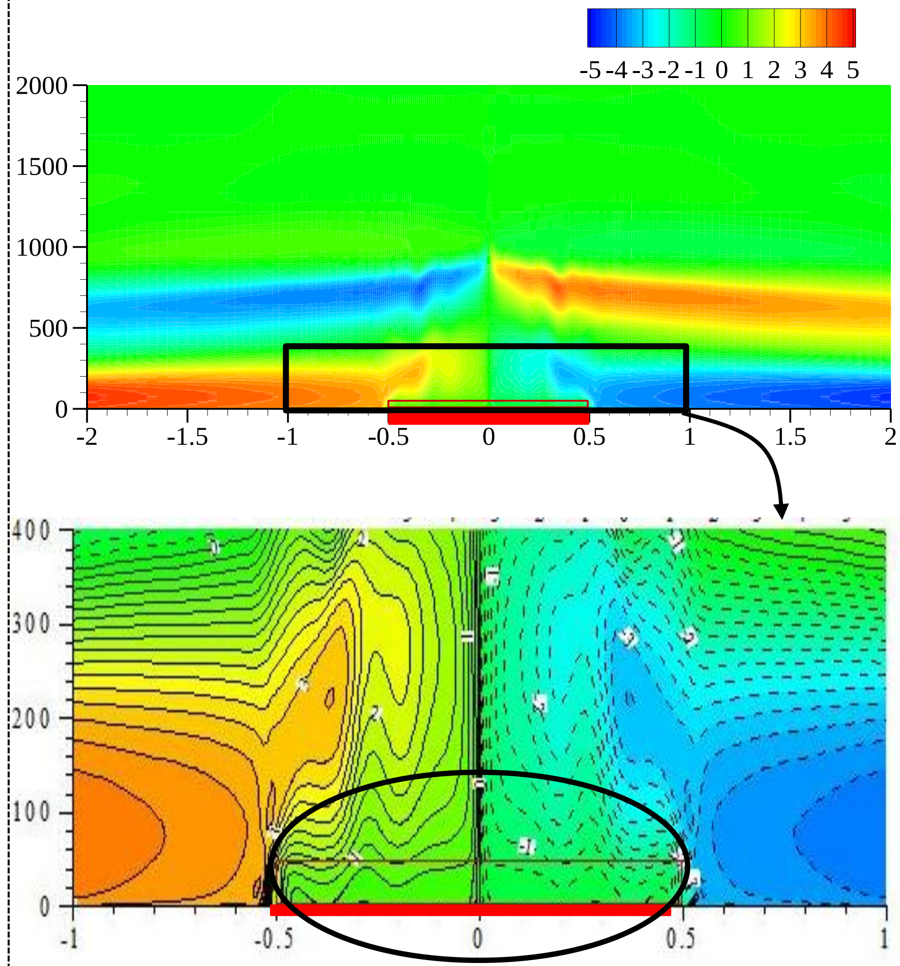


Quasi-steady UHIC– comparing a flat city and a porous city

Flat city

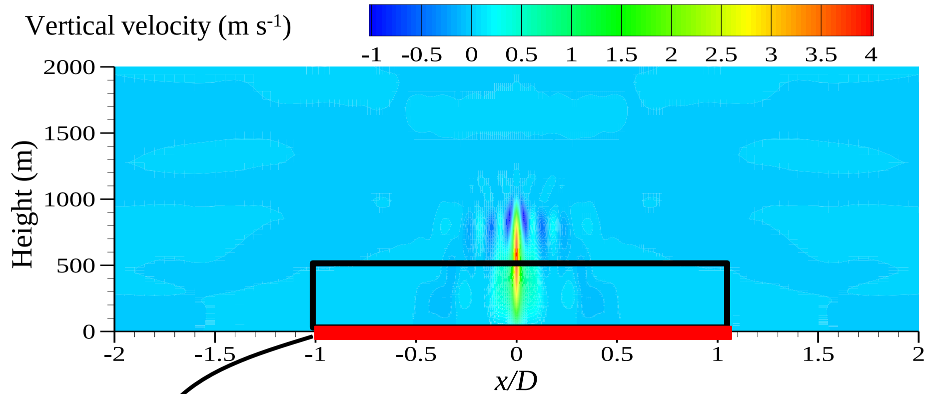


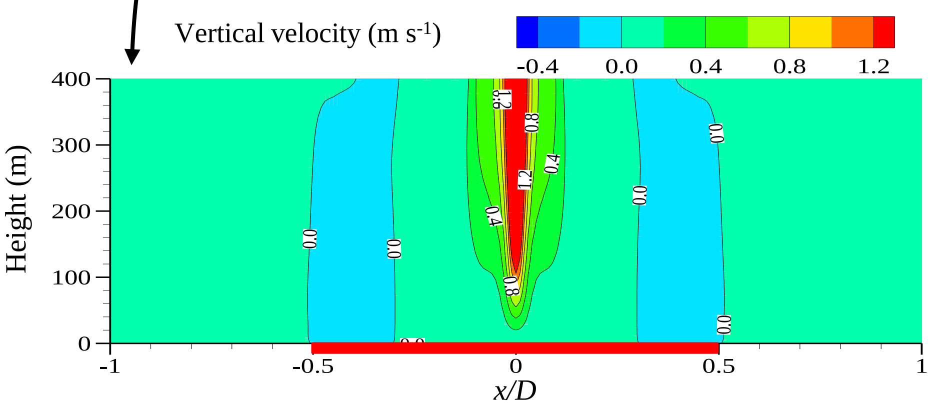
Porous city (Porosity= 0.75 $\lambda_p = 0.25$)



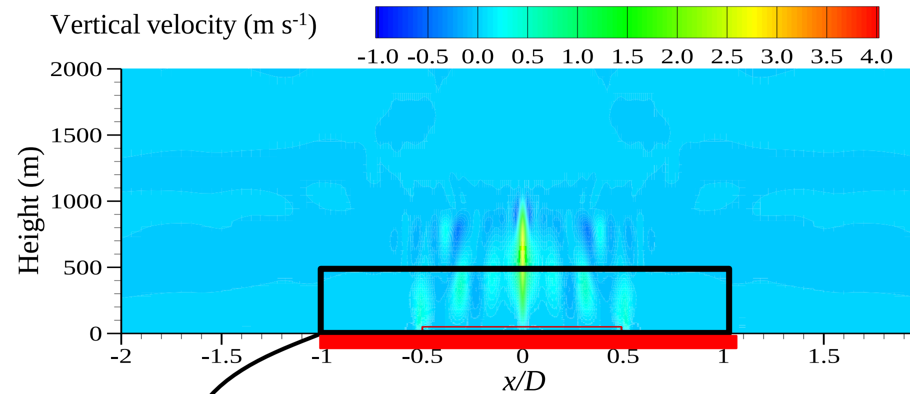
Quasi-steady UHIC– comparing a flat city and a porous city

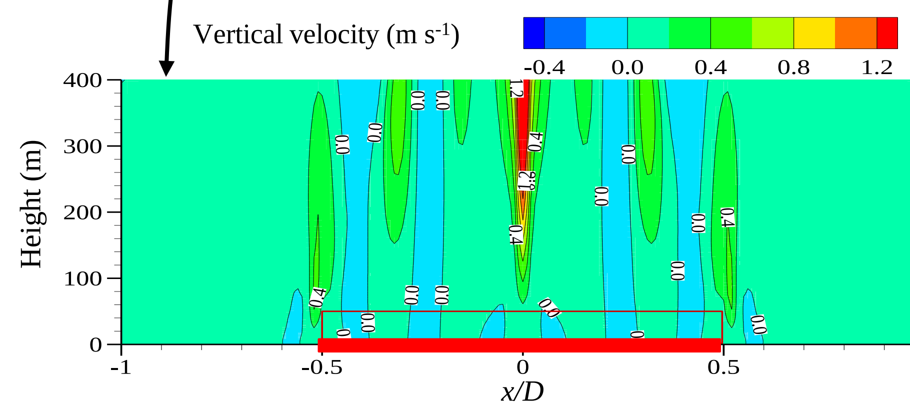
Flat city





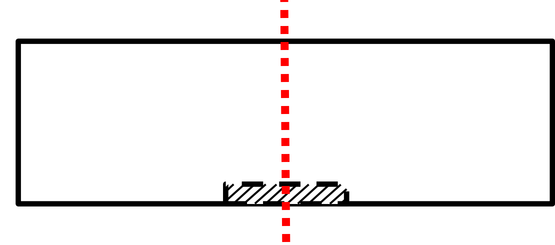
Porous city (Porosity= 0.75 $\lambda_p = 0.25$)

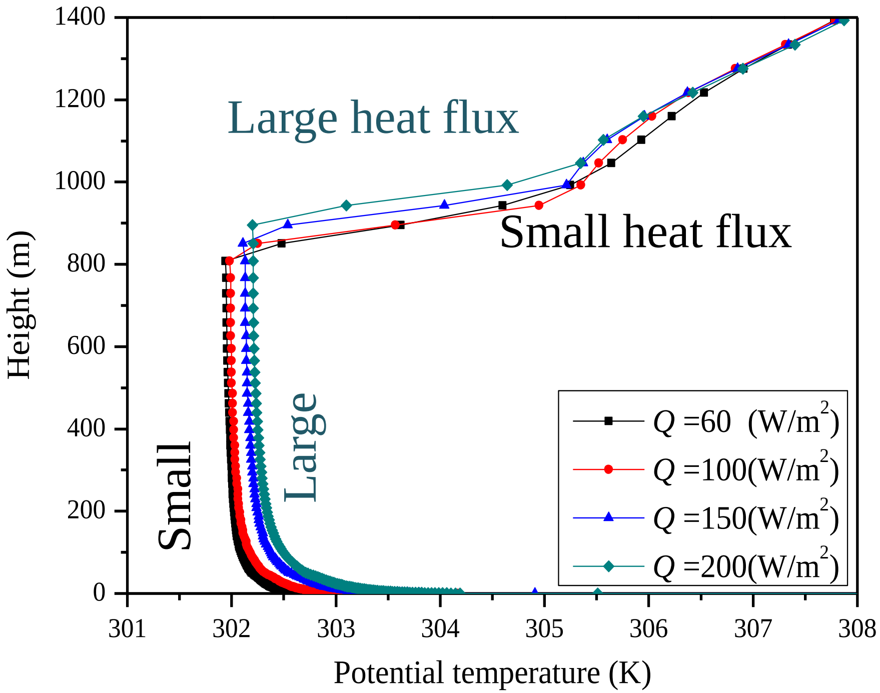


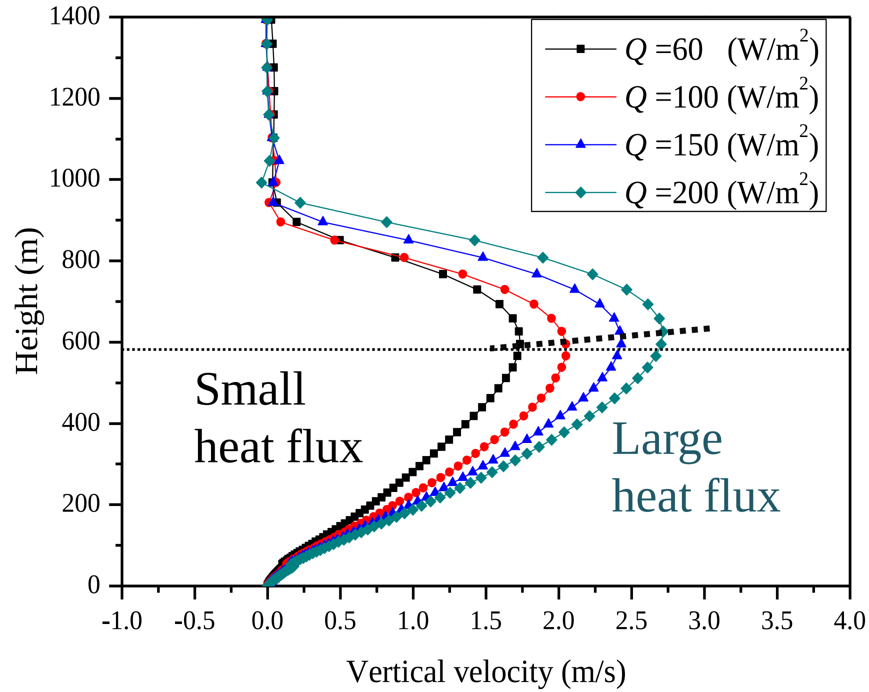


Single upward flow ⟷ Multiple upward flows

Quasi-steady UHIC – effect of heat flux

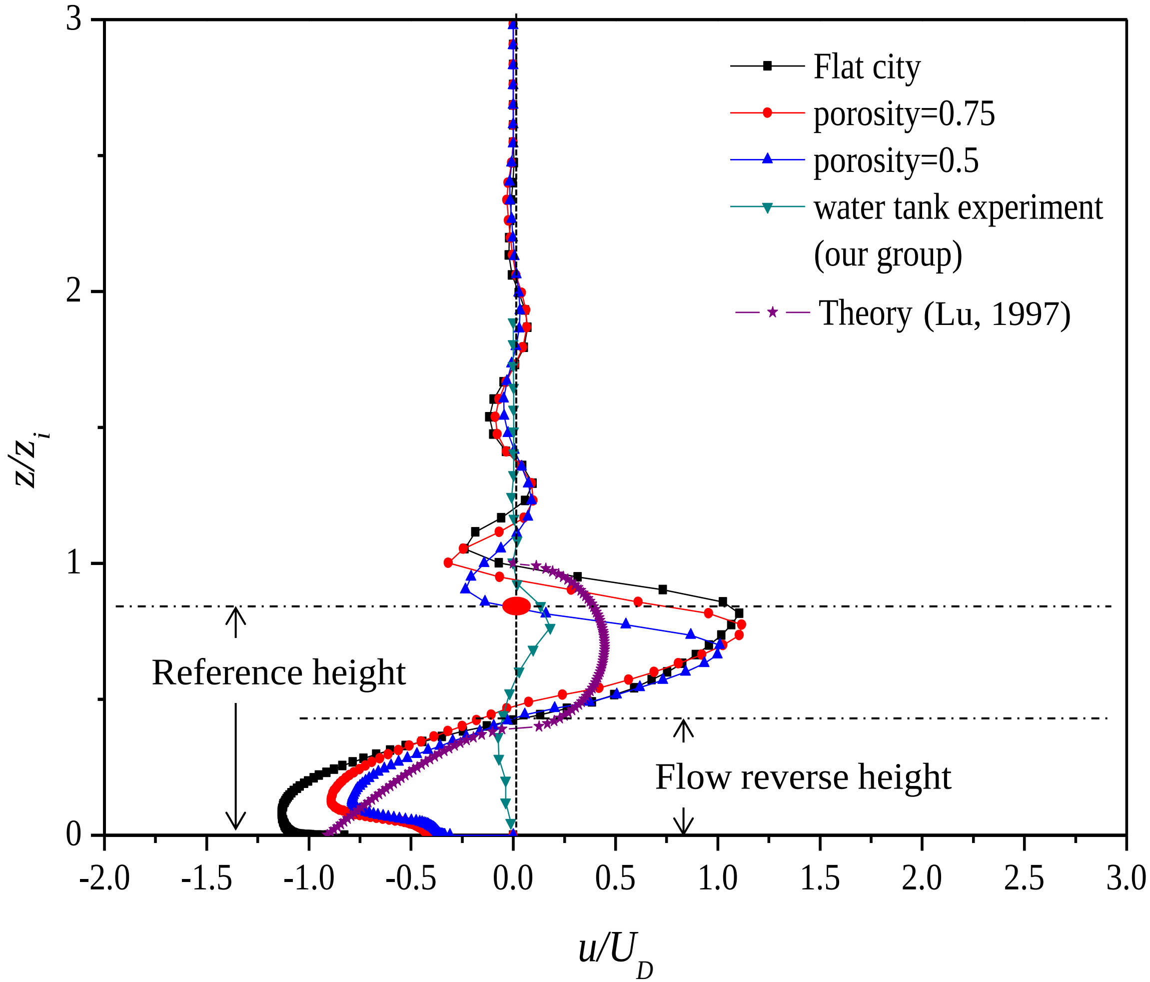






- When the sensible heat flux is larger, the mixing height is higher, vertical velocity is larger, the height of the maximum vertical velocity is higher, and the UHIC is stronger.

Comparing with water tank experiment



$$\text{Relative reverse height} = \frac{\text{Reverse height}}{\text{Reference height}}$$

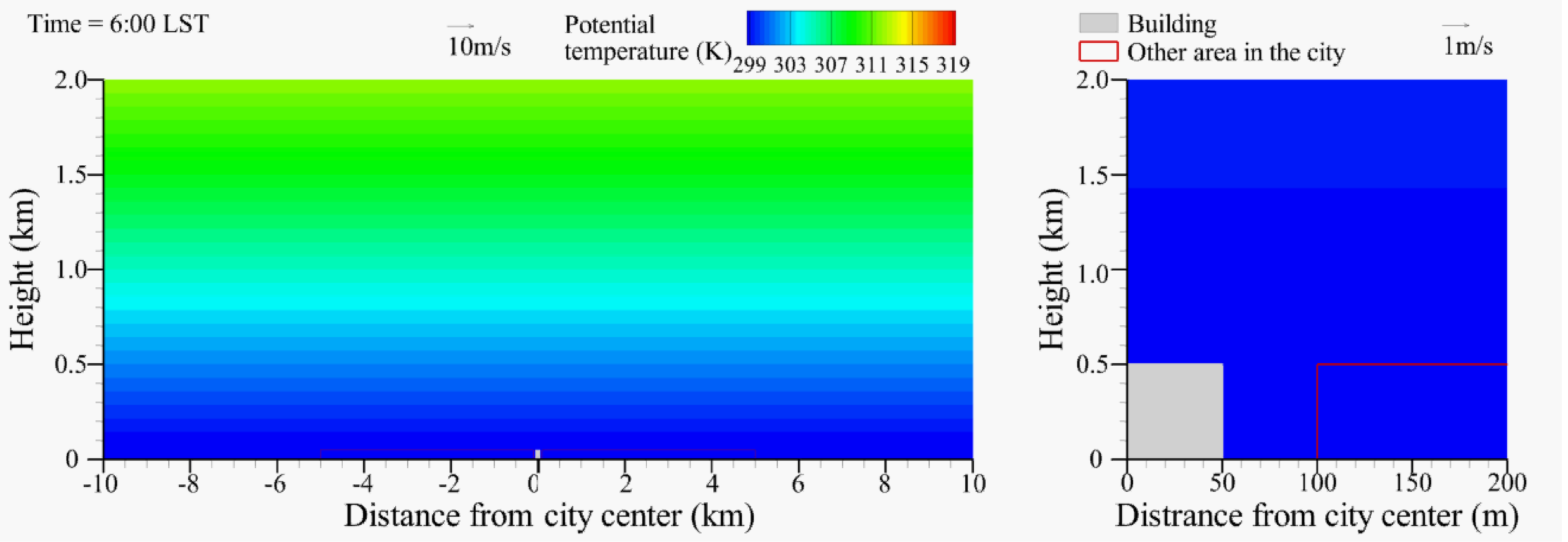
Case	Relative reverse height
ϕ=1.0 (Theory)	39.5%
ϕ=1.0 (Flat city)	42.6%
ϕ=0.75	50.3%
ϕ=0.5	51.3%
ϕ=0.8 *	55.6%

Increase

* water tank data from Yan Yifan

- Our water tank model produced a relatively lower scaled flow, which agreed with other similar studies in the water tank, needs to be further studied.

Preliminary result: simultaneously consider the environment around buildings and city climate



The proposed model could simultaneously simulate the wind and thermal environment around several specific buildings and the basic dynamics in the whole meso-scale area.

In the future, the details around the building will be analyzed.

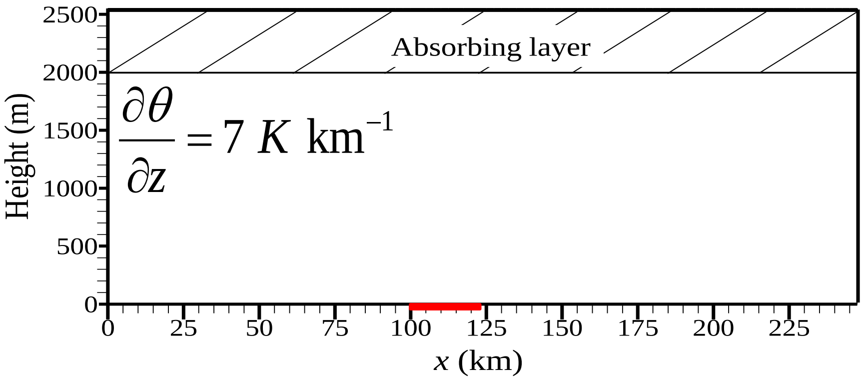
Summary

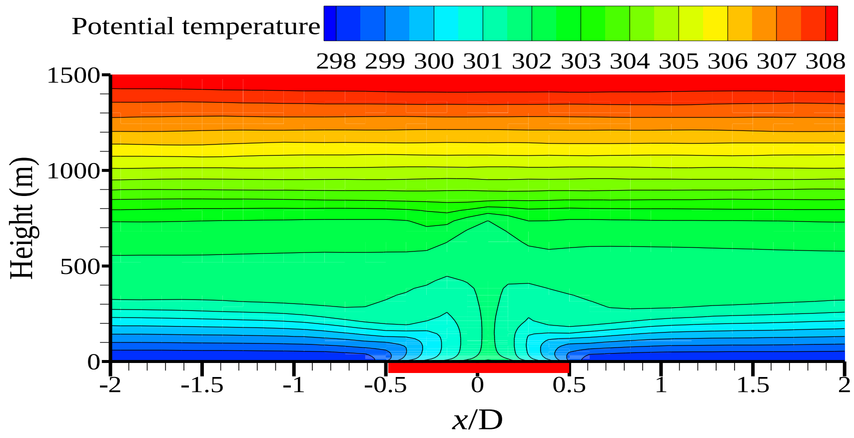
- When the city is introduced by porous media, the velocity in the city decreases, the neck of the plume increases, and multi-upward flows are observed.
- Even when the background wind is zero, the velocity in the city is not zero due to the UHIC.
- The mixing height simulated by CSCFD agrees well with other data in literature.
- Dense cities also increase the relative reverse height at the edge of the city.
- Further data will be needed, and validation of the code for synoptic wind conditions is also needed.

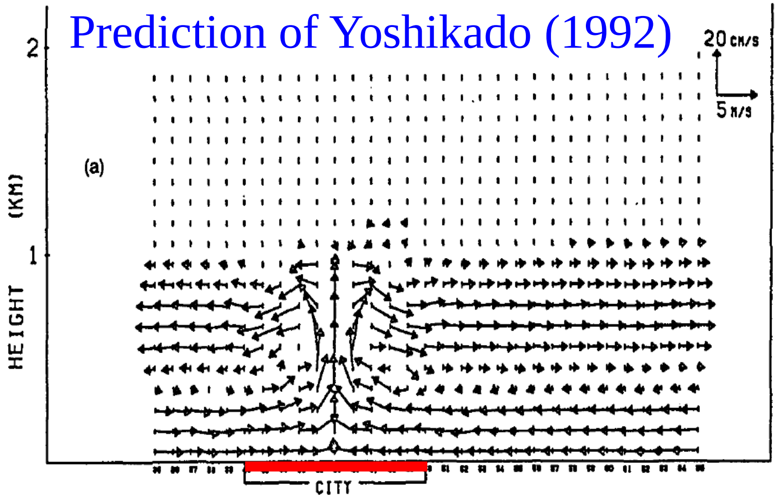

THANK YOU

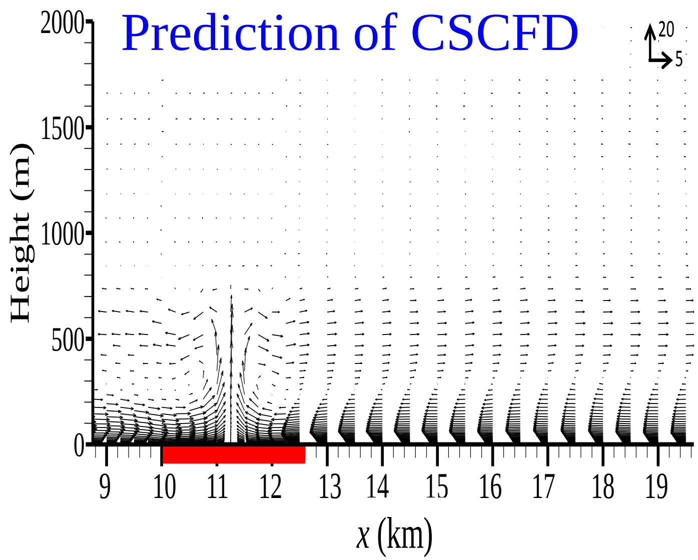
Comparing with meso-scale model

The general plume features are well predicted.

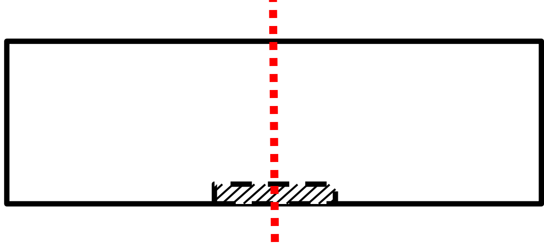


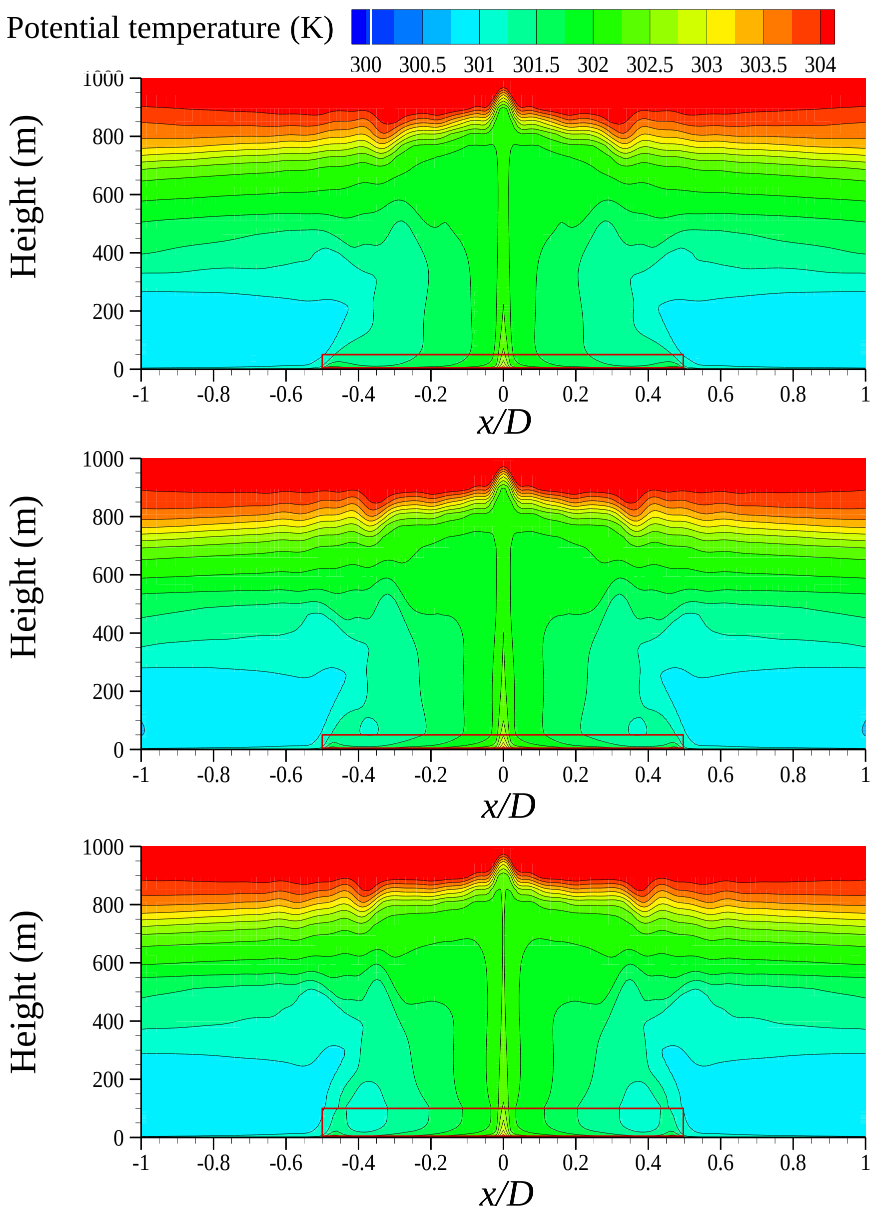


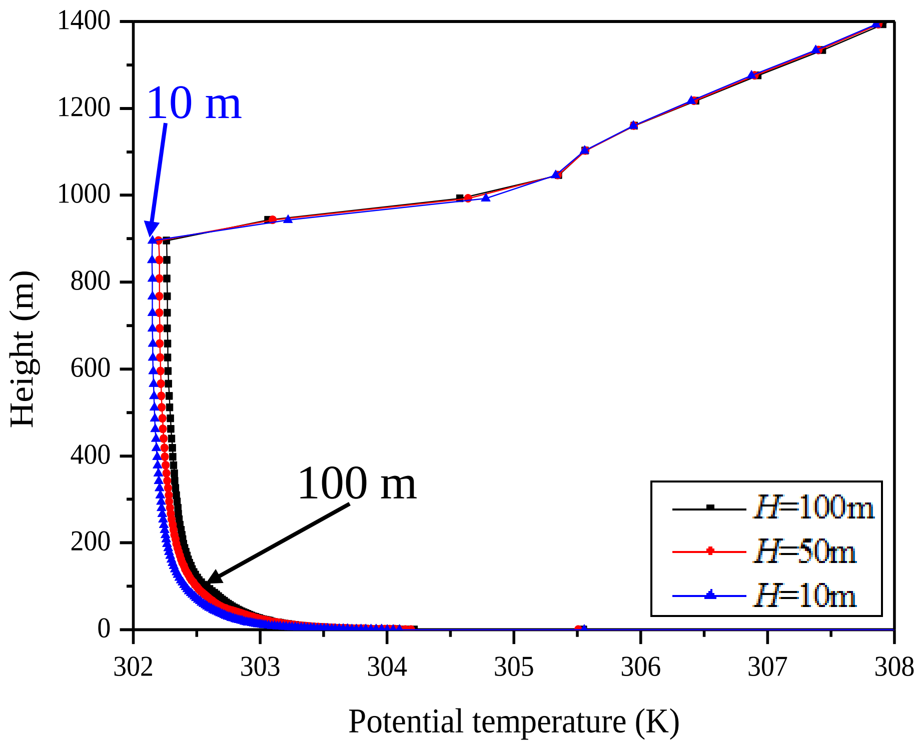




Quasi-steady UHIC – effect of city

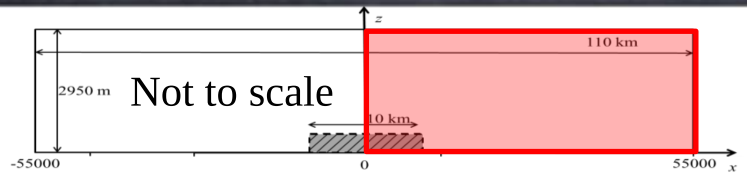






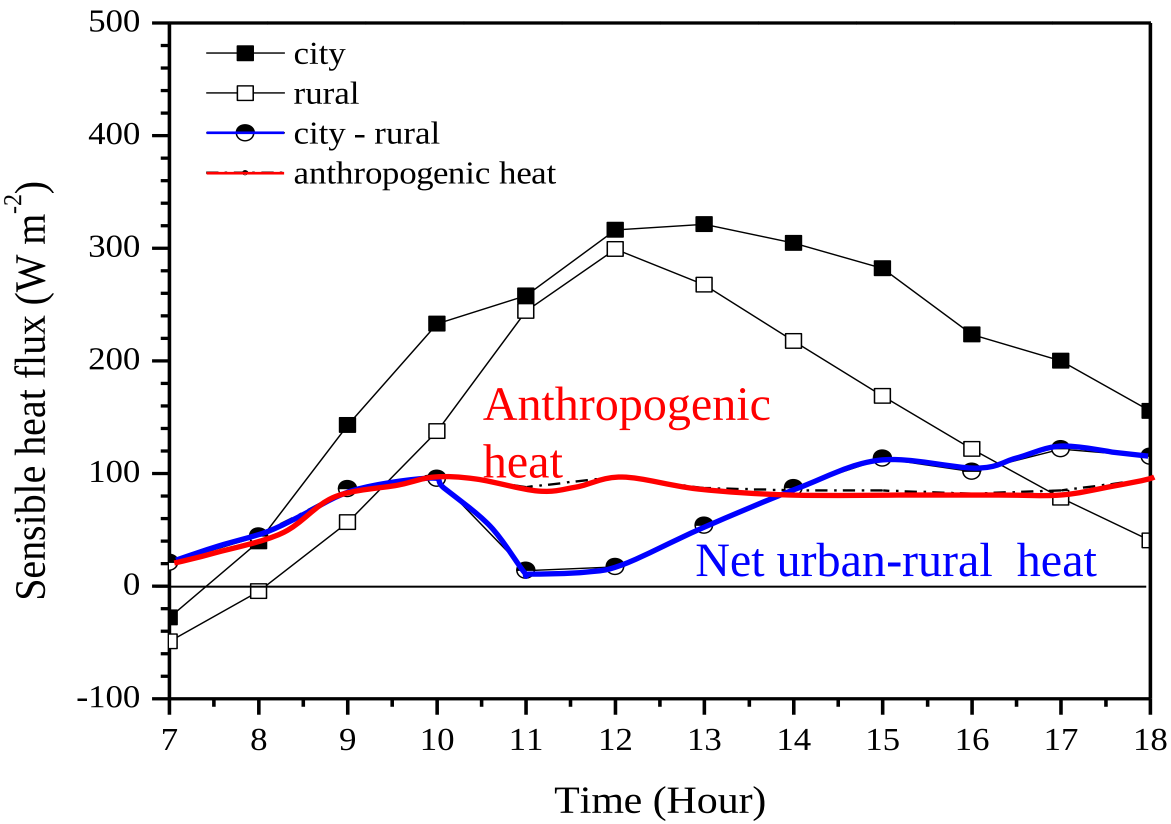
- The city height does not affect the mixing height, but affects the entrainment at the lower part.

Application 2 – 12-hour evolution of daytime UHIC



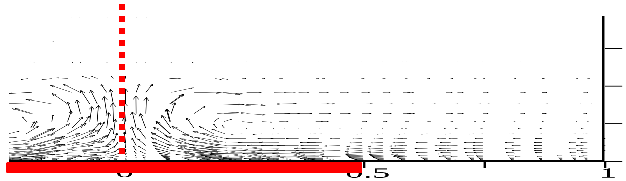
The same cities in Application 1 is used here.

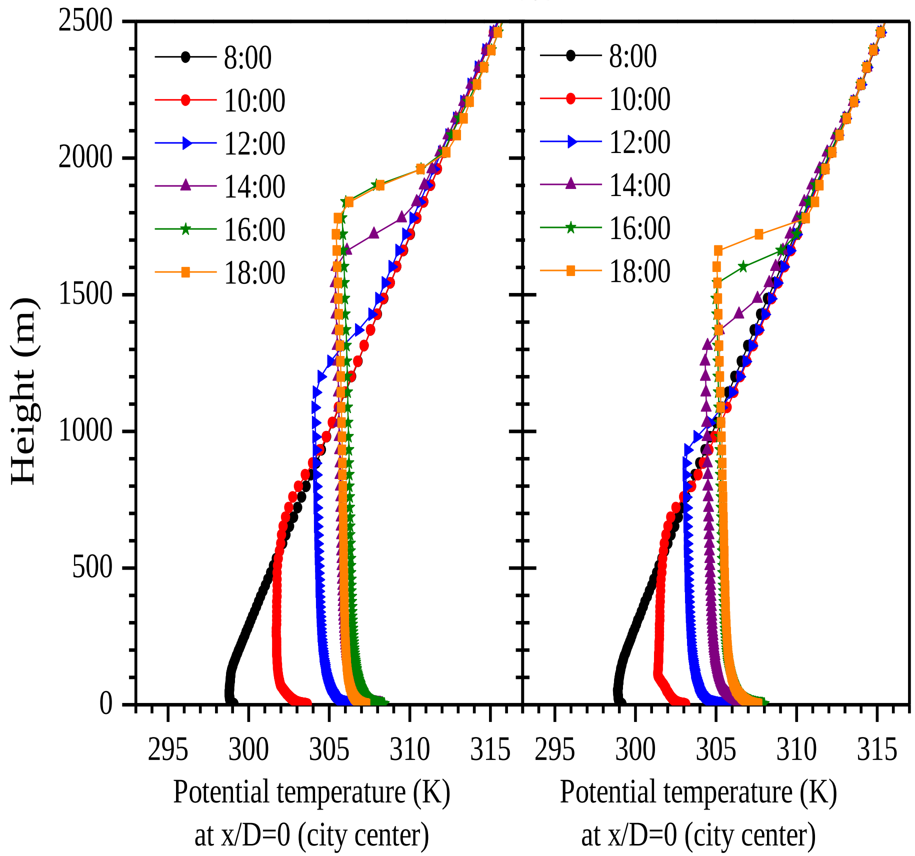
The sensible heat flux is partitioned with 25% in the porous air and 75% at the ground surface (assuming porosity is 0.75).



The 12-hour profiles for the sensible heat flux (calculated from the new 24-hour boundary condition)

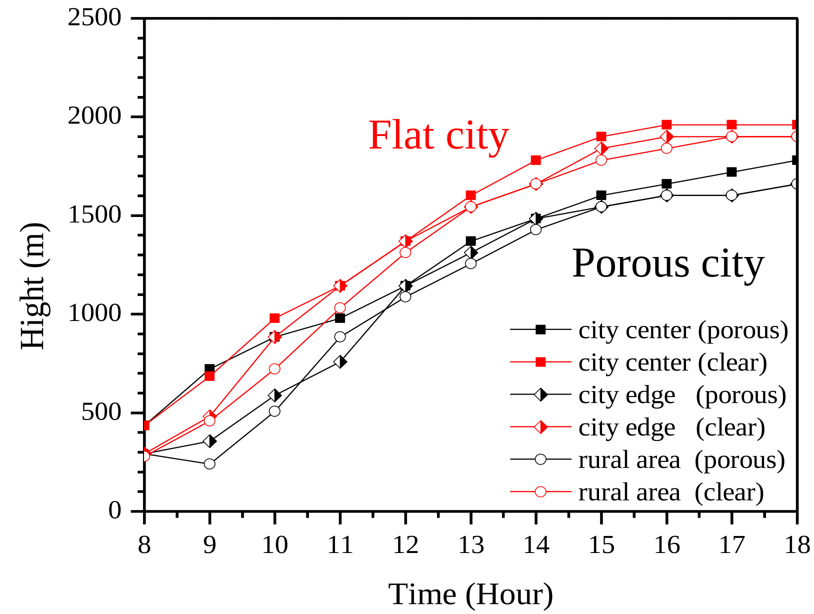
Application 2 – 12-hour evolution of daytime UHIC – Comparing mixing height for a flat city and a porous city.





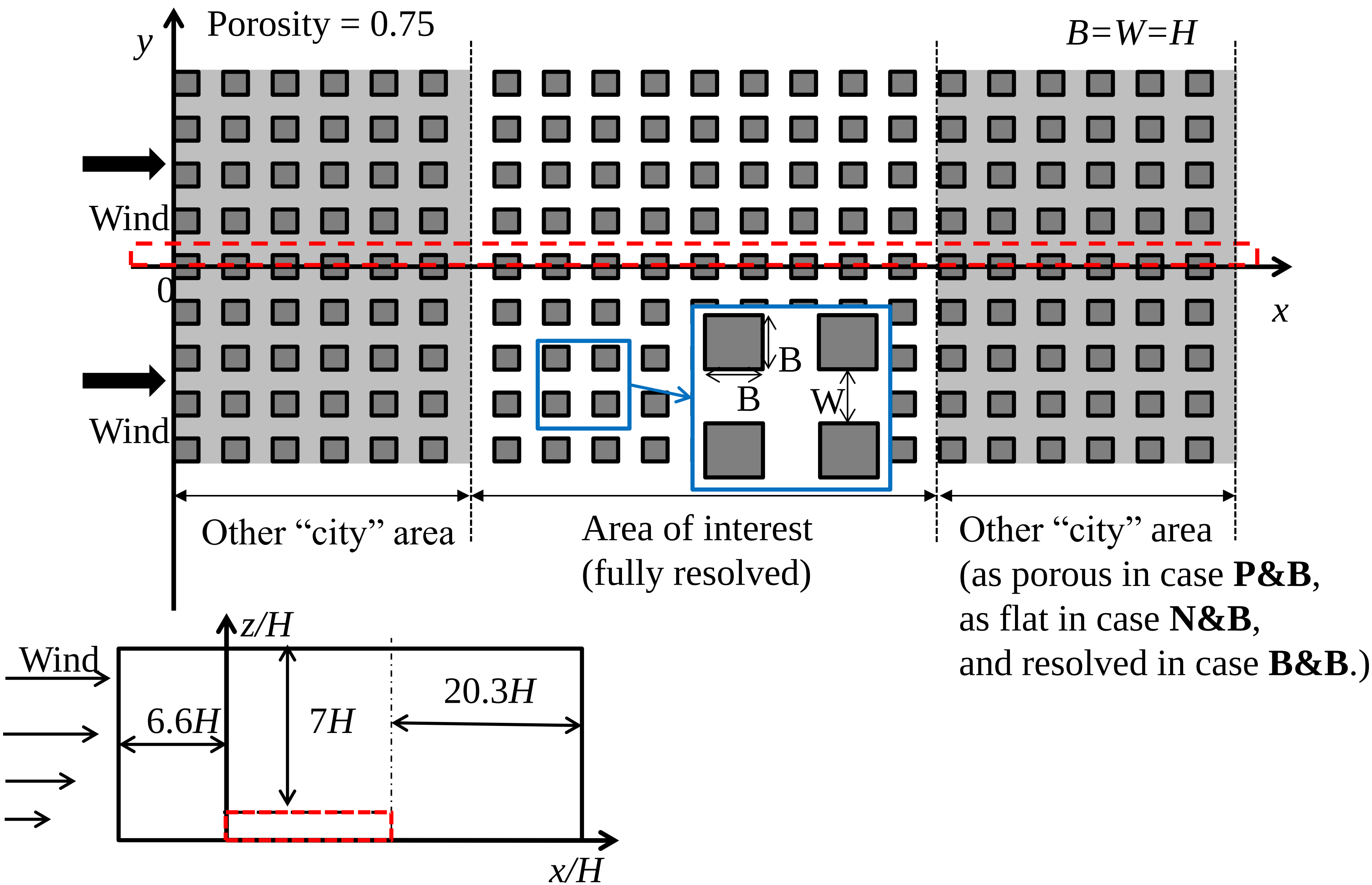
Flat city

Porous city

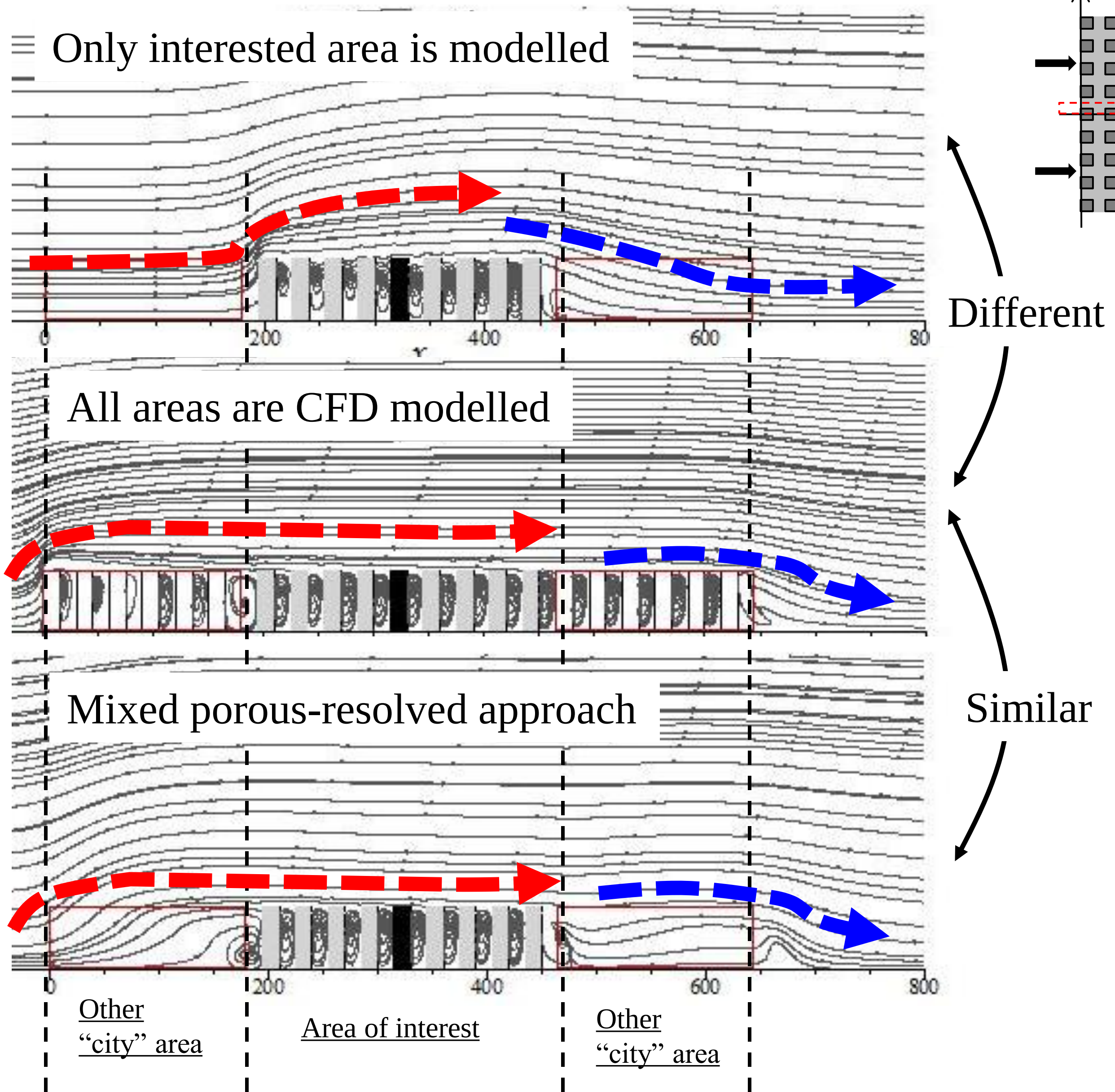


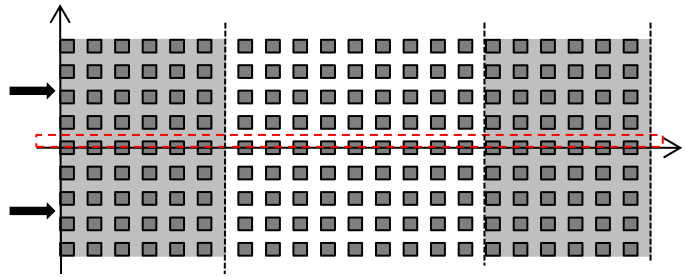
The porous city has a lower mixing height due to flow resistance, which leads to multiple smaller plumes.

The mixed porous-resolved approach



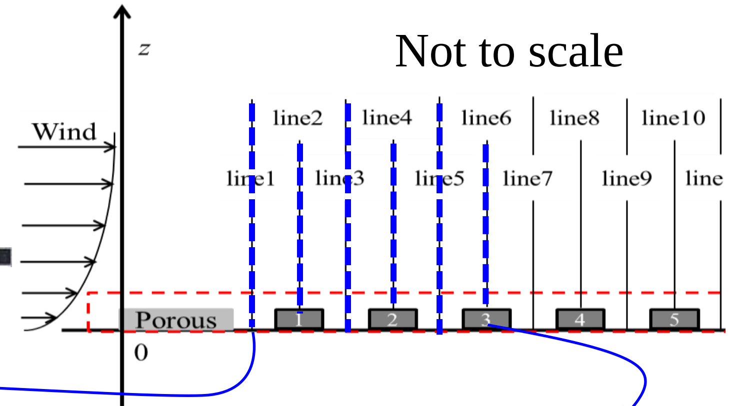
The mixed porous-resolved approach



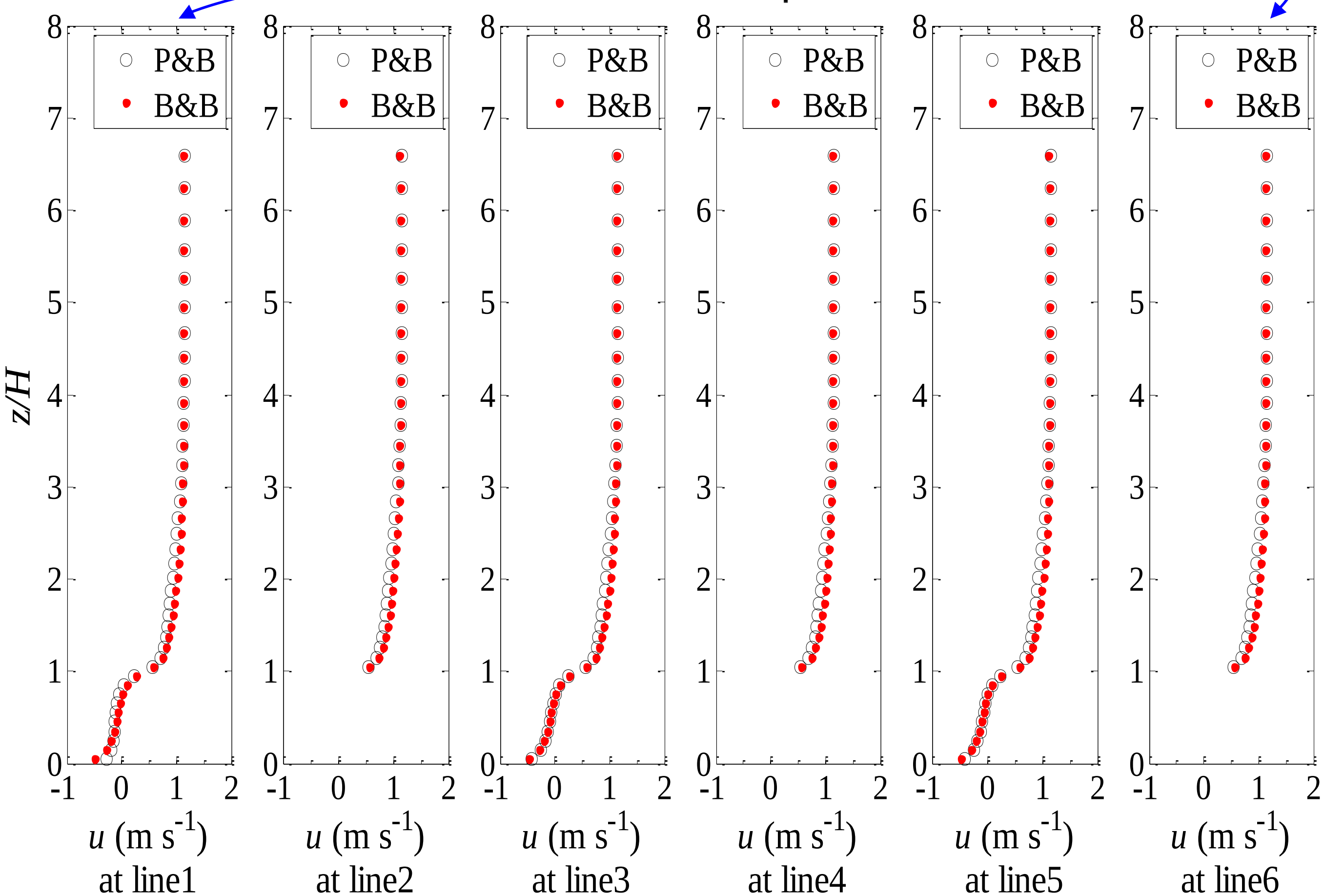


The mixed porous-resolved approach can predict well the airflow pattern in the other "city" areas and its impact on micro-scale flows in the area of interest

Verification - Comparing the mixed porous-resolved approach with full resolution in an ideal city



The mixed approach produces nearly identical *u*-velocities with the fully resolved approach.

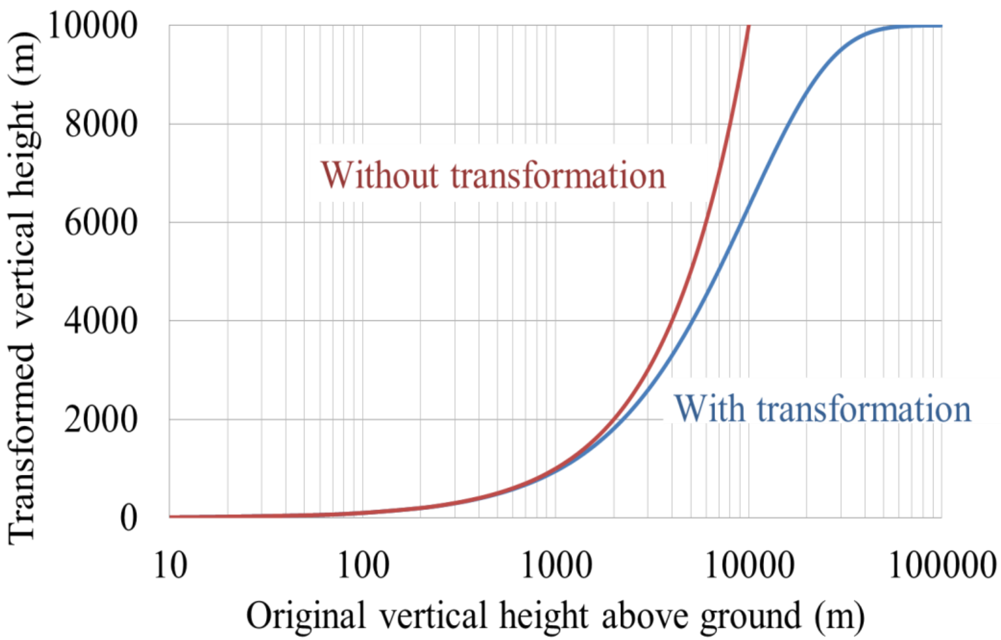


CSCFD Coordinate transformation

Based on the pressure equation,
The transformation coefficient is

$$\xi = \frac{1}{z}\left(\frac{g}{R\Gamma}-1\right)\ln\left(1-\frac{\Gamma z}{T_0}\right)$$

Γ is the temperature lapse rate



After the transformation:

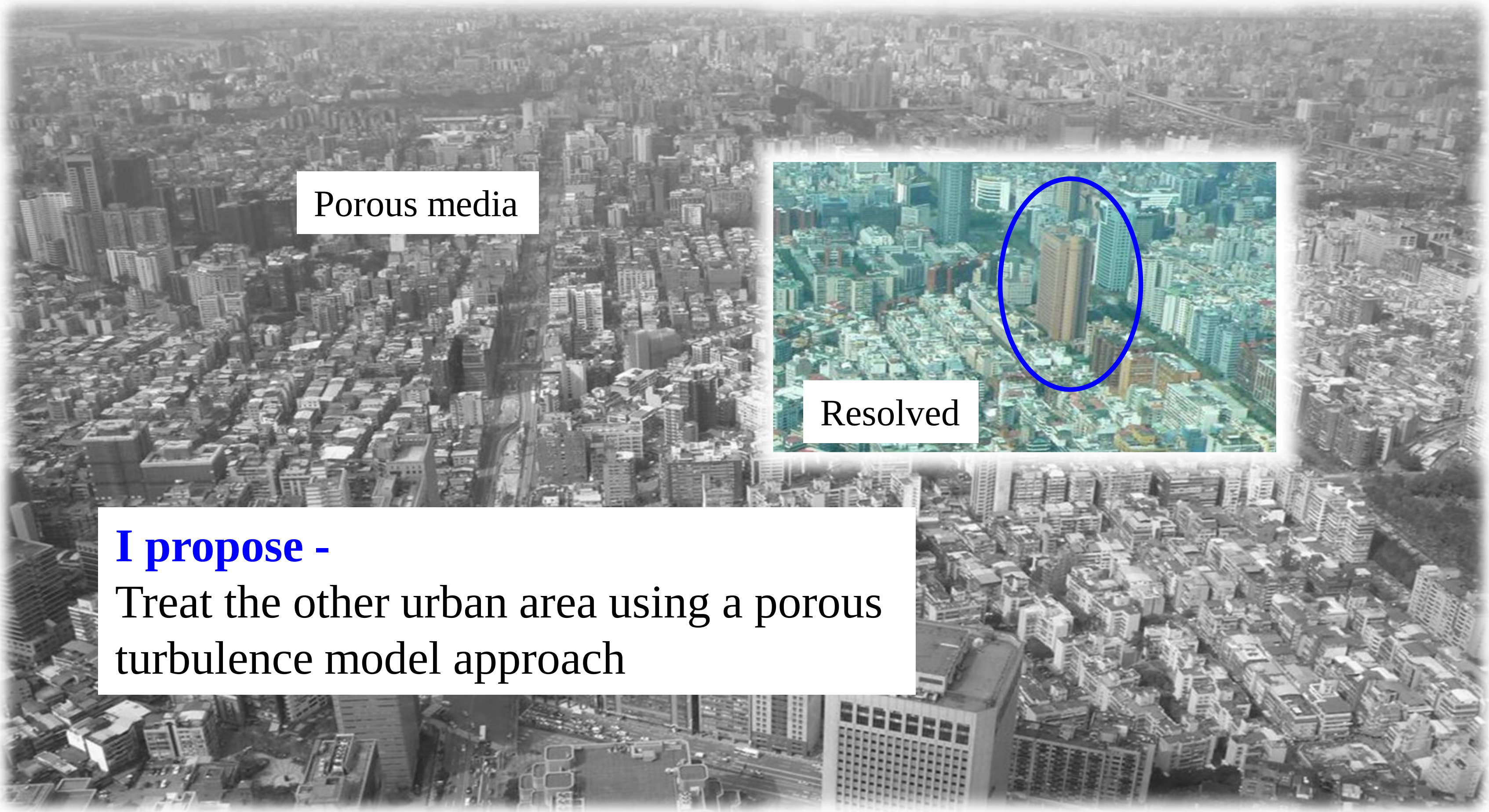
$$z = \frac{1}{\xi}\ln\left(1+\xi z_n\right)$$

$$u_n = u; \quad \rho_n = \rho + \rho_0\left(1-e^{\xi z}\right) \quad w = e^{-\xi z} w_n$$

$$v_n = v; \quad T_n = T + \Gamma z; \quad p_p = e^{\xi z} p_n$$

Kristóf et al. (2009)

Methodology -- City-Scale CFD (CSCFD)



I propose -
Treat the other urban area using a porous turbulence model approach

Introduction

The urban heat island circulation is a multi-scale flow problem, which includes

- the mesoscale (~10^3 km)
- the city scale (10^1~10^3 km)
- the local scale (10^{-3}~10^1 km)

How to analyze the UHIC's effect in the city/around the buildings ?

by modeling the environment around several buildings in isolation?
or by modeling the whole city with simple parameterizations?
or by a modified CFD model -- City-Scal CFD (CSCFD)?