Large-Eddy simulation of Pollutant Plume Dispersion over 2D Idealized Street Canyons

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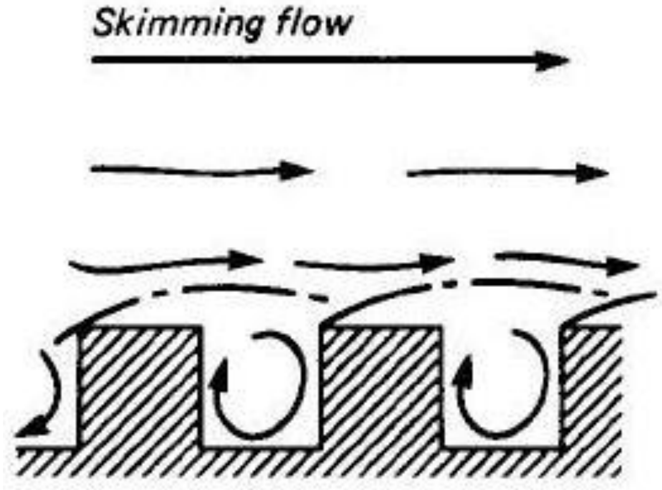
OUTLINE

- Introduction
- Methodology
- Results & Discussion
  - Pollutant transport below and around roof level
  - Pollutant dispersion in the urban boundary layer (UBL)

INTRODUCTION

In a developed city like Hong Kong, the building-height-to-street-width ratio (aspect ratio, AR) is large. In case the wind is flowing perpendicular to the street canyon (worst case), the flow falls into skimming flow regime in which flesh air cannot entrain into the street canyons by mean flow.



Source: Oke, T. R. "Street Design and Urban Canopy Layer Climate." *Energy and Buildings*, 11 (1988)

A satellite photo of Mong Kok, Hong Kong

Any methods to remove/dilute the pollutants better?

Source: Google map

OBJECTIVES

The core objectives of this study are:

- Develop a platform to calculate pollutant dispersion over idealized 2D street canyons using LES.
- Examine how 2D urban roughness affects the flow structure and the pollutant dispersion in the urban boundary layer (UBL).
- Elucidate the pollutant removal mechanism when the prevailing flow is perpendicular to the street canyons.

Introduction to CFD

- Currently, three types of models are commonly used for resolving/modeling fluid turbulence.
  - k-ε model (RANS based)
  - Large-eddy simulation (LES)
  - Direct numerical simulation (DNS)

Model	k-ε model	LES	DNS
Accuracy	Lower		Higher
Computational cost	Relatively cheap	Expensive	Very expensive

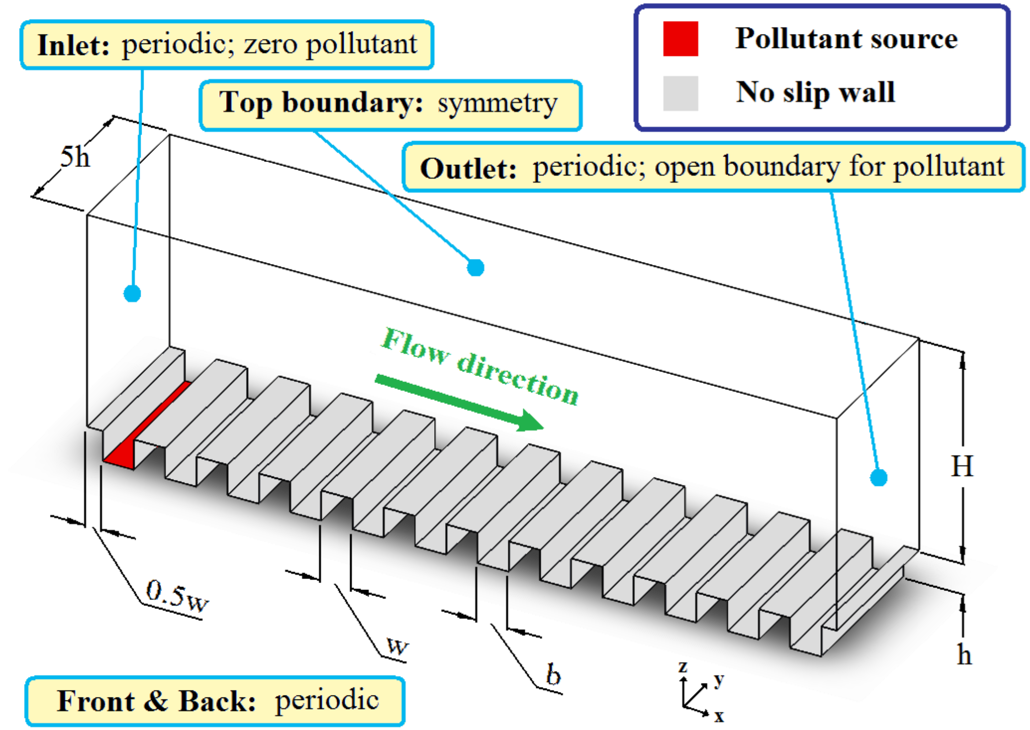
THE REASON OF USING LES

- Pollutant dispersion is strongly correlated with atmospheric turbulence
  - k-ε model assumes isotropic turbulent kinetic energy (TKE) but the turbulence structure over 2D roughness is highly anisotropic

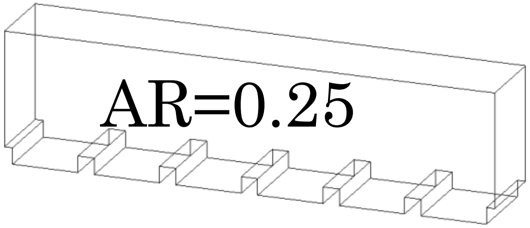
- Study of turbulence structure of individual components (i.e.: stream-wise fluctuation component) could not be achieved using k-ε turbulence model.

Methodology

- Computational domain and boundary conditions



AR=1.0



AR (Aspect ratio) = h/b

Model Details

- CFD code used: OpenFOAM 1.7.0
- Turbulence model: Large-eddy simulation
  - With One-equation TKE subgrid-scale (SGS) model
- Velocity-pressure coupling: PISO
- Reynolds number: ~10,000
- Pollutant source: Constant concentration source

List of completed computations

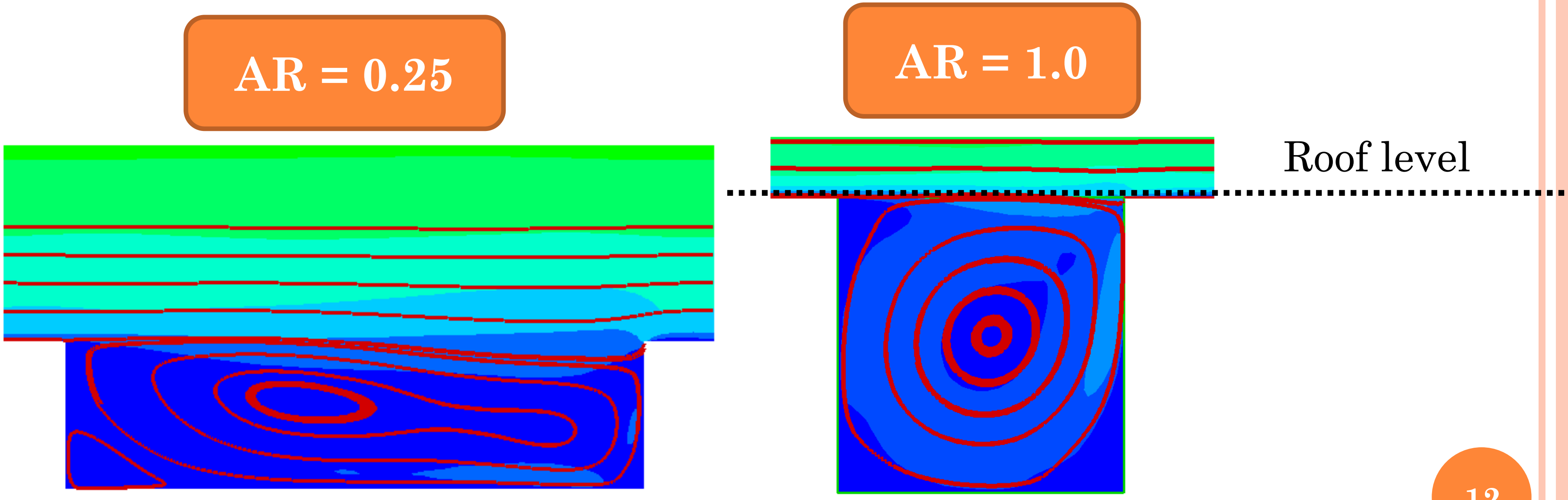
Model	AR = 1	AR = 1 (Coarse)	AR = 0.25
No. of canyons	12	12	6
No. of grids in each canyon (x,y,z)	32×160×32	16×80×16	128×160×32
No. of grids in UBL (x,y,z)	768×160×280	384×80×140	960×160×280
Total No. of grids	~36M	~4.5M	~47M
Computation time	5 months	2 months	6 months

Results & Discussion

Pollutant transport below & around roof level

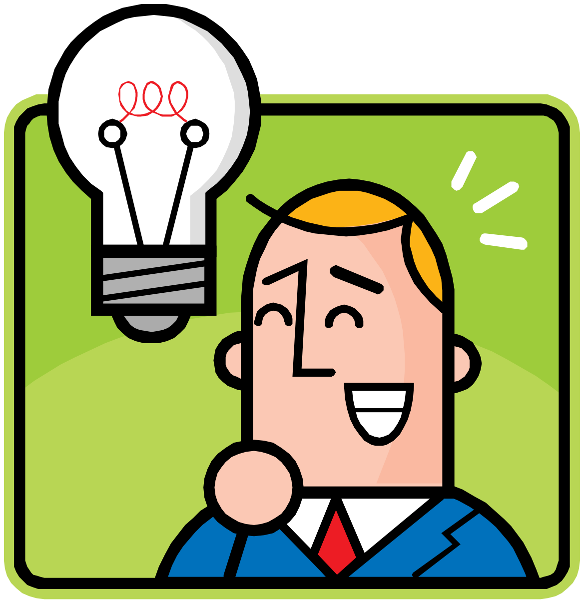
STREAMLINES

- Primary recirculation is formed within each street canyon.
- The mean wind in the UBL do not go into the street canyons.



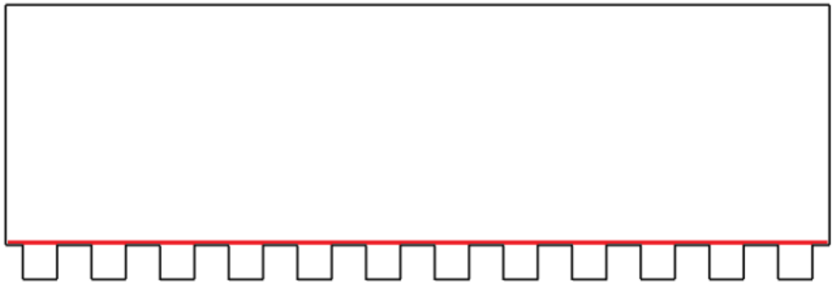
Cheng *et al*. (2008) pointed out that:

In skimming flow regime, the pollutant removal is mainly governed by turbulent transport instead of the mean wind using RANS *k*-*ε* turbulence model.



POLLUTANT REMOVAL

- The following slides show the vertical pollutant flux along the roof level. Here, the three types of flux are:



$$Mean\ \ flux = \left\langle \overline{w} \right\rangle \left\langle \overline{\phi} \right\rangle / \Phi / U$$

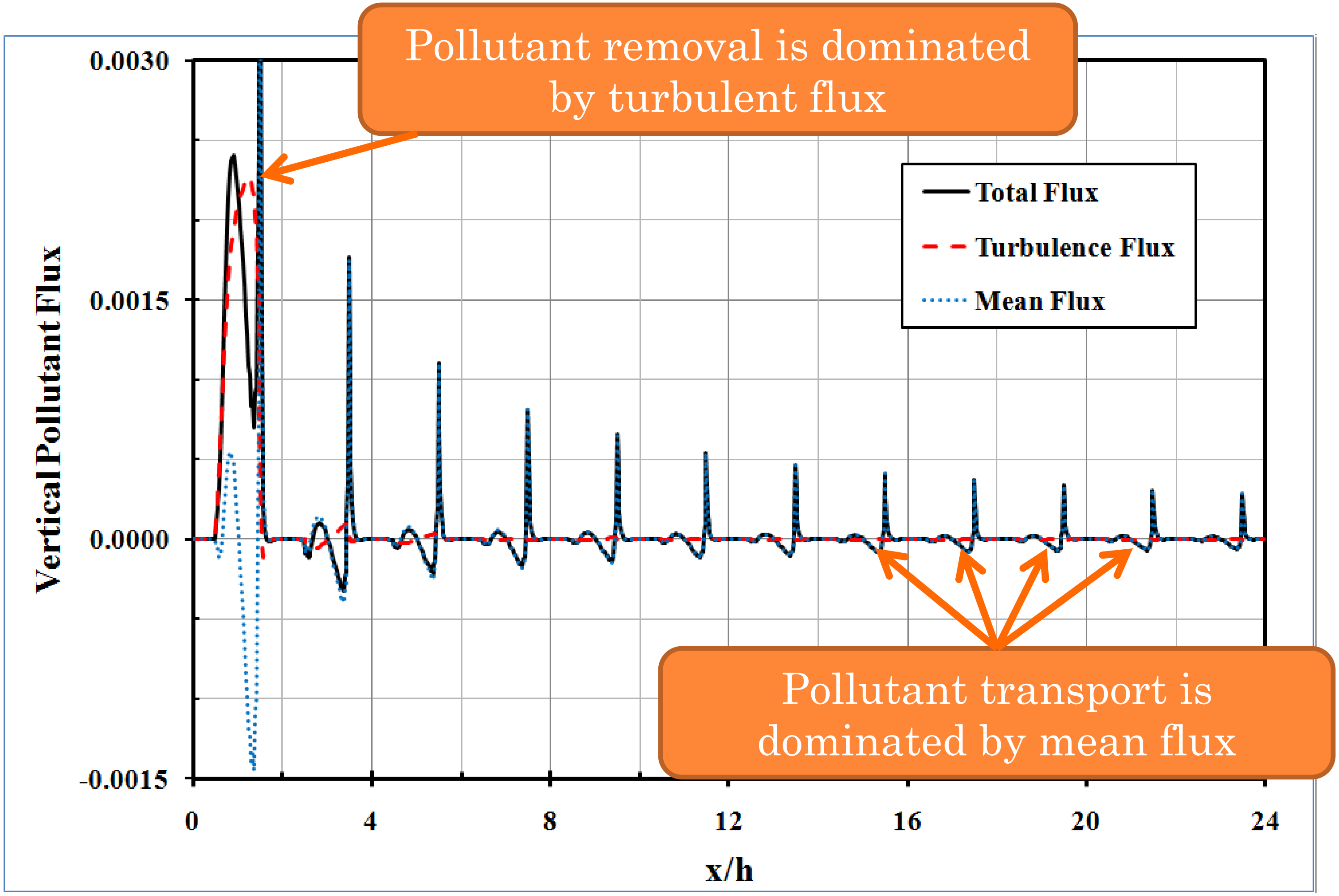
$$Turbulent\ \ flux = \left\langle w''\phi'' \right\rangle / \Phi / U$$

$$Total\ \ flux = \left\langle \overline{w} \right\rangle \left\langle \overline{\phi} \right\rangle / \Phi / U + \left\langle w''\phi'' \right\rangle / \Phi / U$$

$\langle \psi \rangle$ *is the spatio-temporal average in the spanwise direction.*

$\psi'' \left(= \psi - \left\langle \overline{\psi} \right\rangle \right)$ *is the deviation from its mean.*

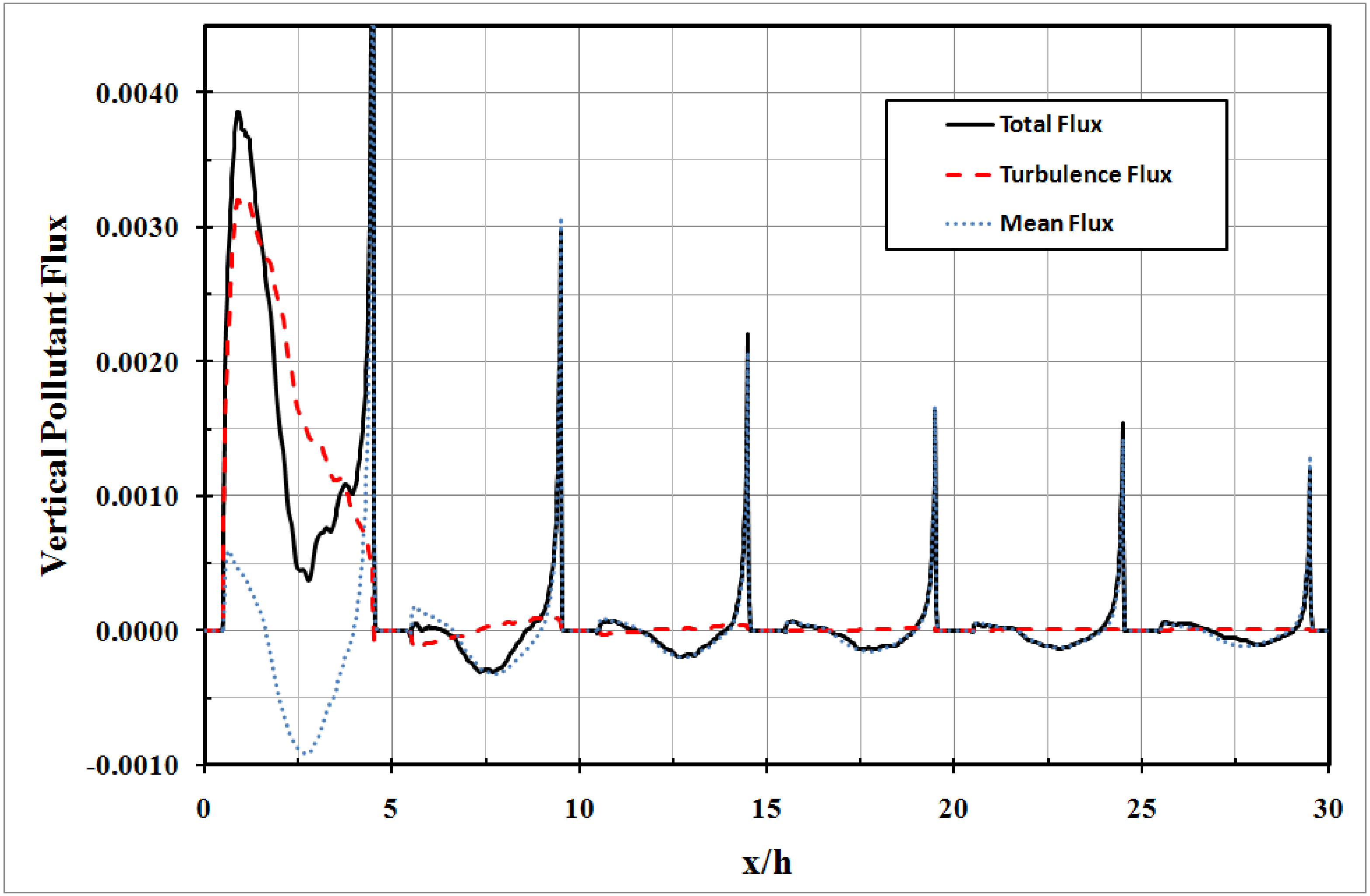
MEAN FLUX VS TURBULENT FLUX ACROSS ROOF LEVEL (AR=1)



Vertical Pollutant Flux

x/h

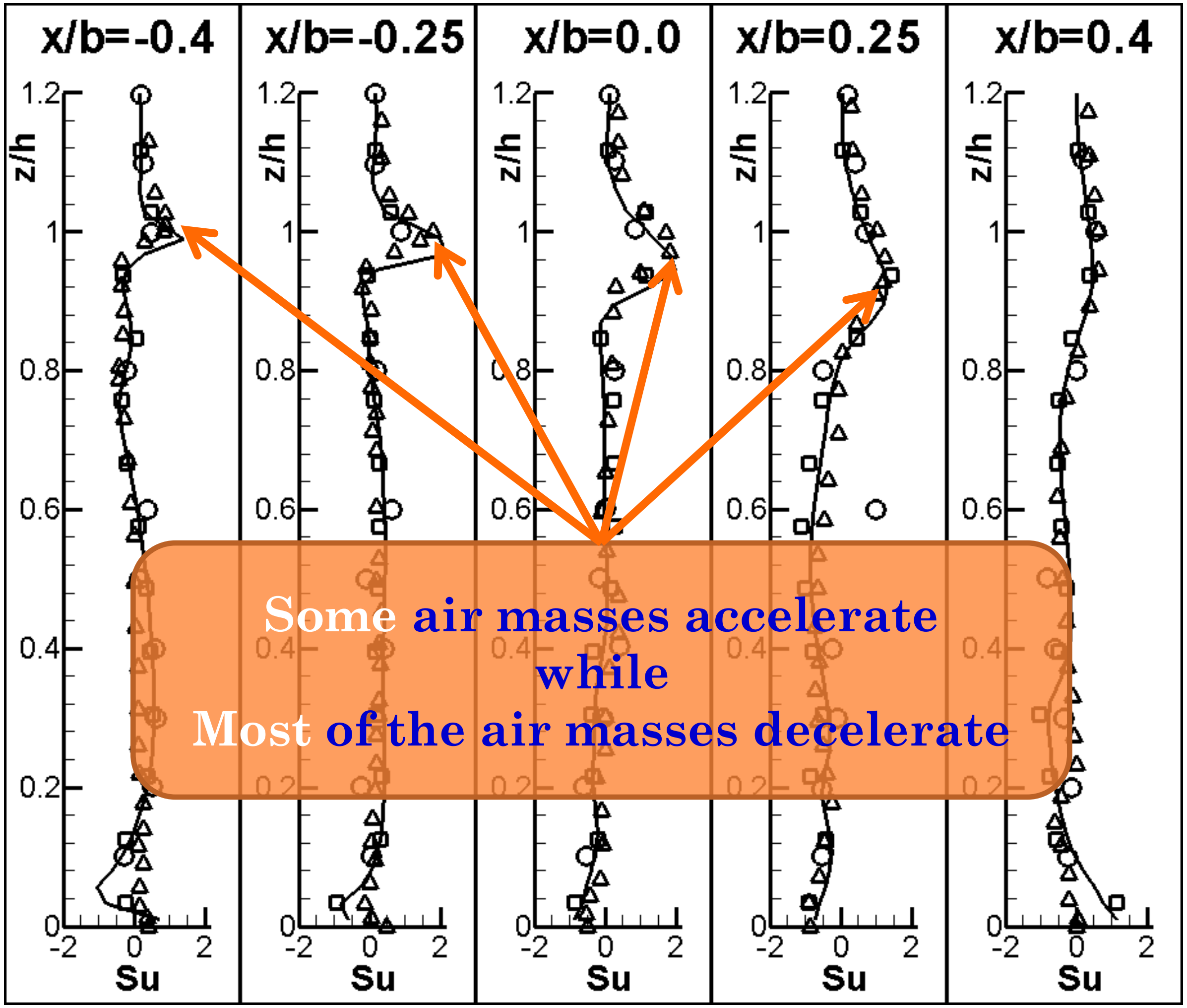
Mean flux vs turbulence flux across roof level (AR=0.25)

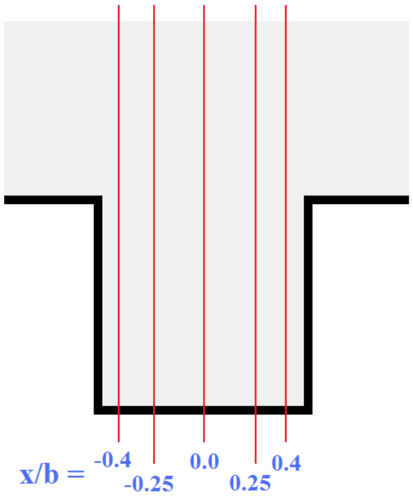


Question

How is the pollutant removed from the street canyons to the UBL?

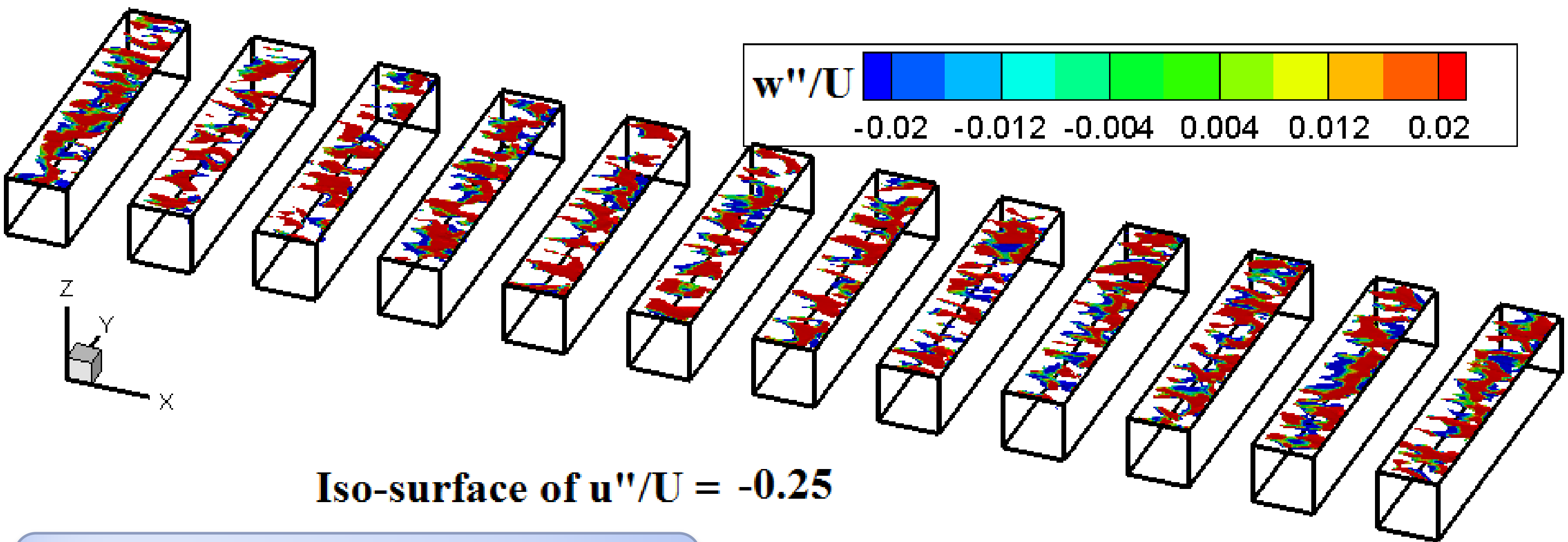
Skewness of u (AR=1)





SNAP SHOT OF ISO-SURFACES OF STREAMWISE FLUCTUATION VELOCITY AT ROOF LEVEL

- Large amount of decelerating, up-rising air masses are located along the roof level.



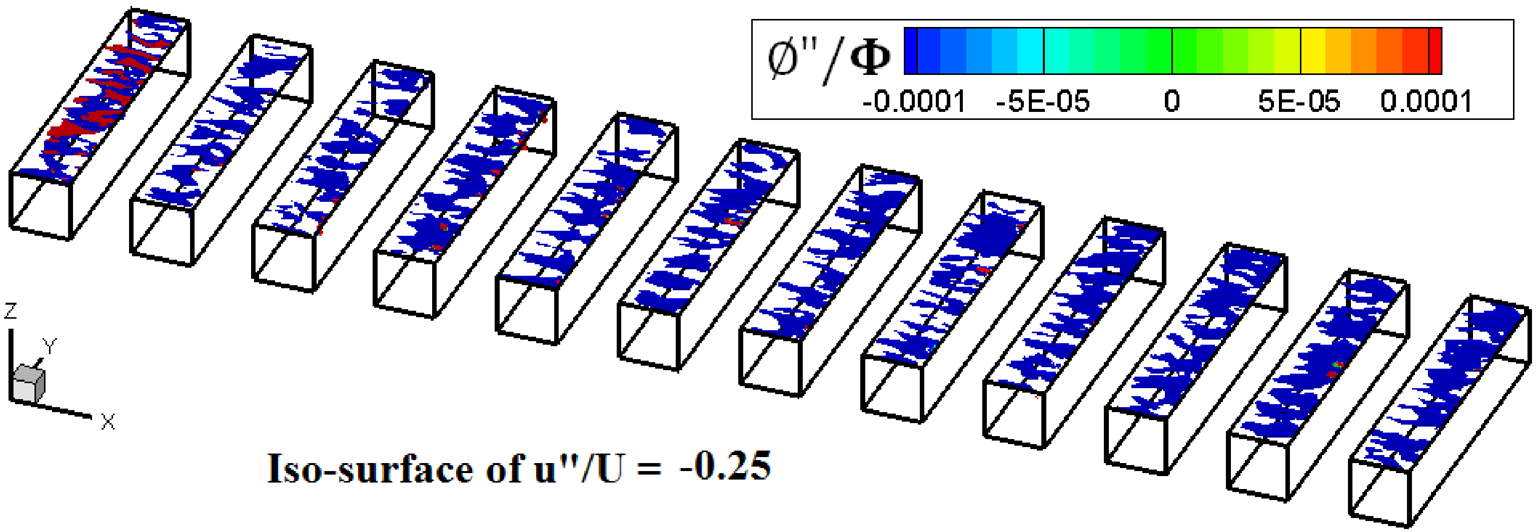
$u'' < 0$ represents deceleration

$w'' \approx w$ at roof level

$\psi''\left(=\psi-\langle\overline{\psi}\rangle\right)$ *is the deviation from its mean.*

COHERENT STRUCTURE AT ROOF LEVEL

- $\phi'' < 0$ occurs in the street canyons without pollutant source.

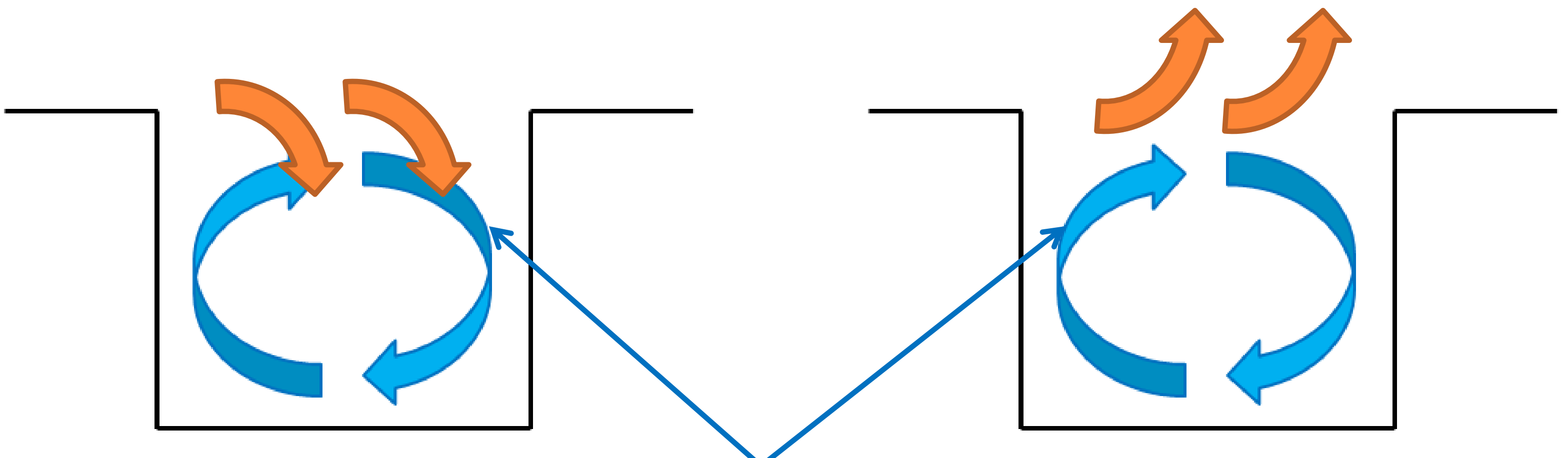


Iso-surface of u''/U = -0.25

REMOVAL MECHANISM

The accelerating air masses ($u'' > 0$) carry the background pollutant into the street canyon by sweeps.

The decelerating air masses ($u'' < 0$) remove the ground-level pollutant to the UBL by ejections.



The primary re-circulation mixes the pollutant within the street canyon.

Removal mechanism

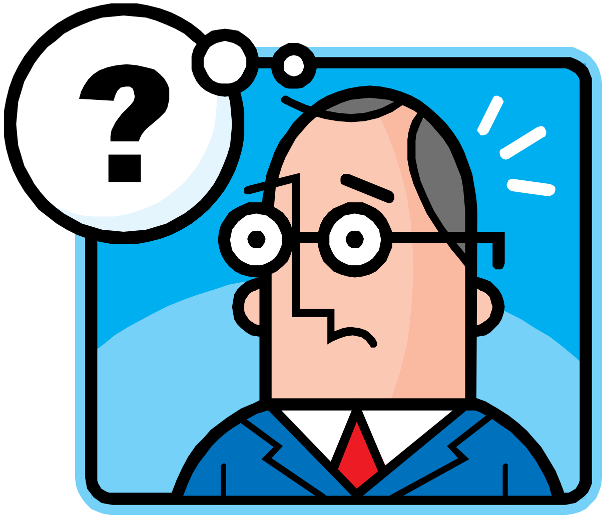
With pollutant sources

Pollutant removal by ejections $>>$ Pollutant entrainment by sweeps

Pollutant removal by ejections $\approx$ Pollutant entrainment by sweeps

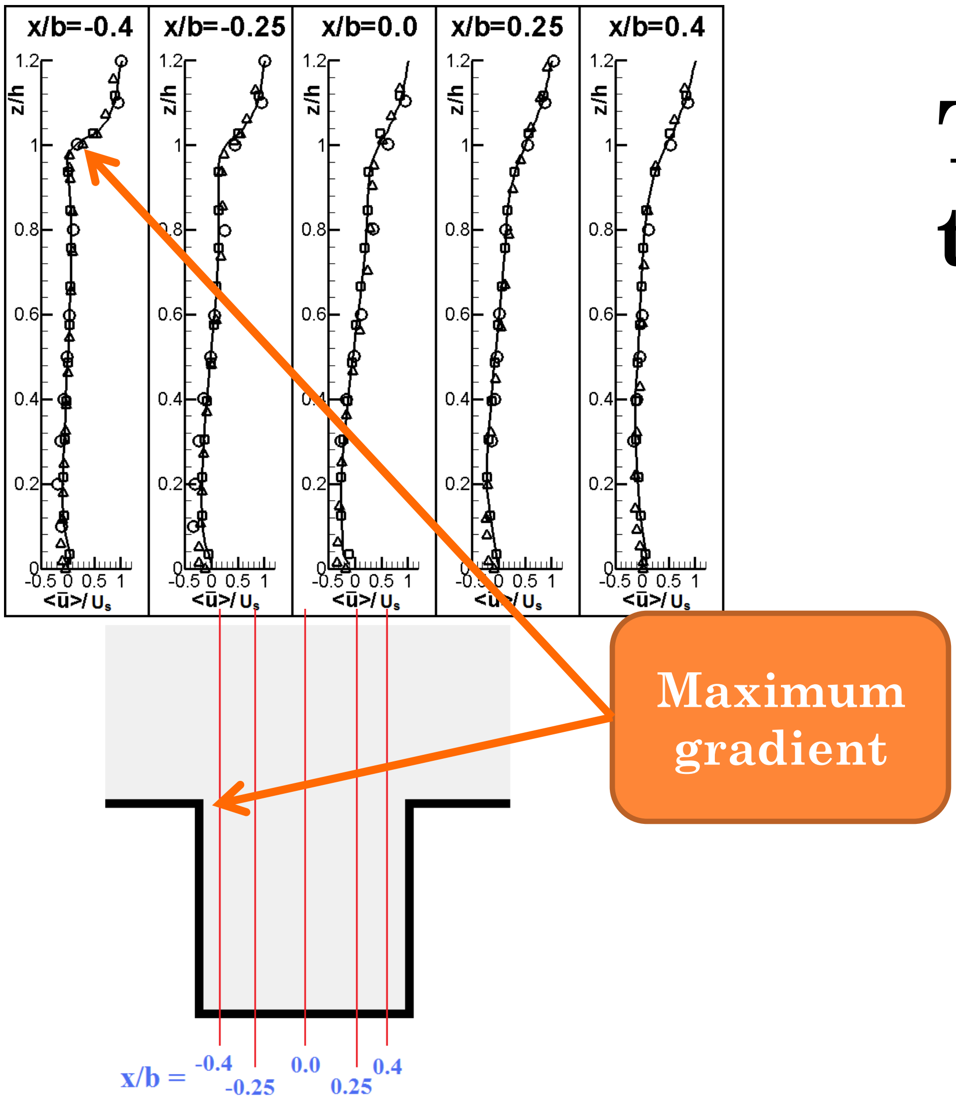
Without pollutant source

Question



Where does the turbulence come from?

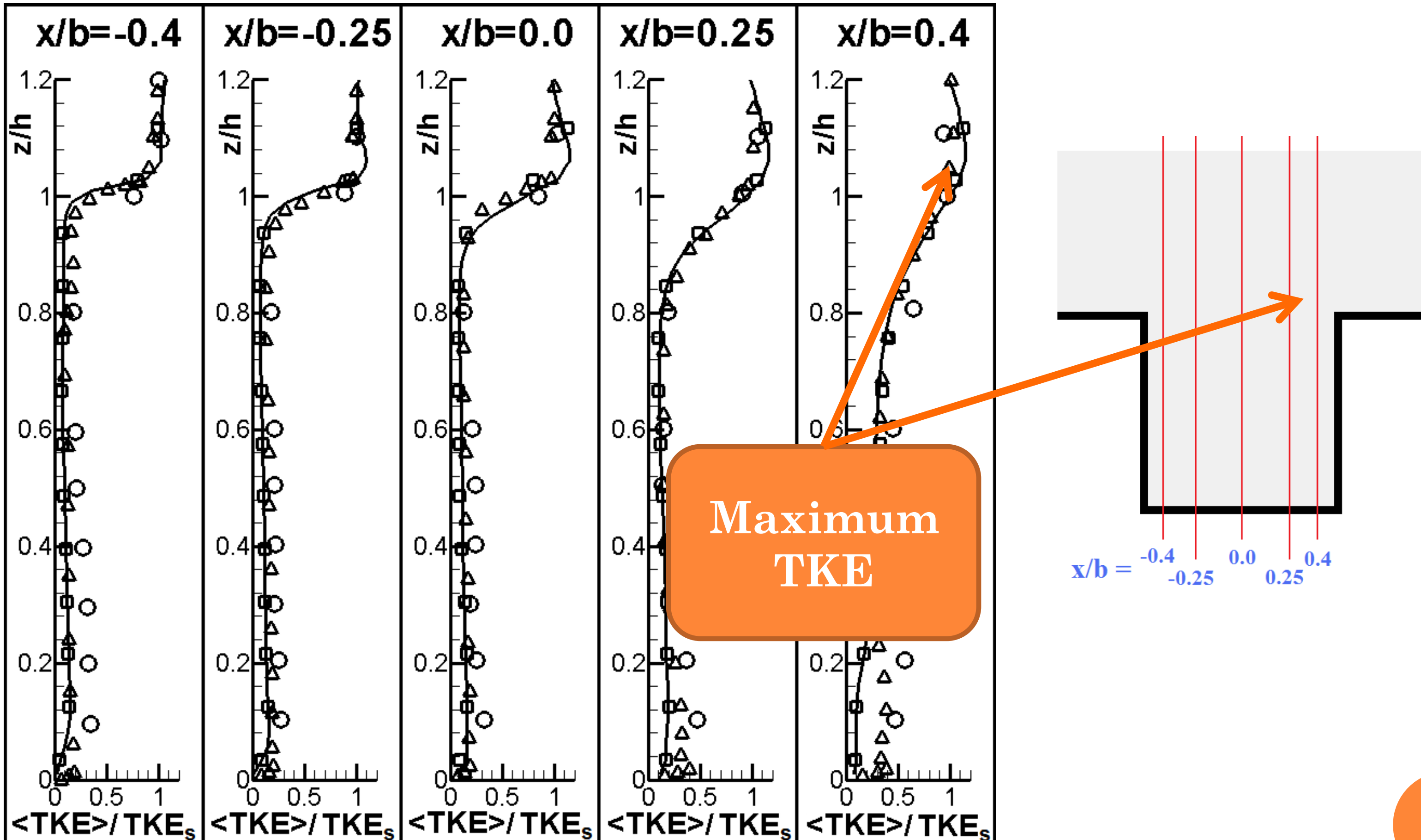
MEAN FLOW VELOCITY (AR=1)



The production term of TKE

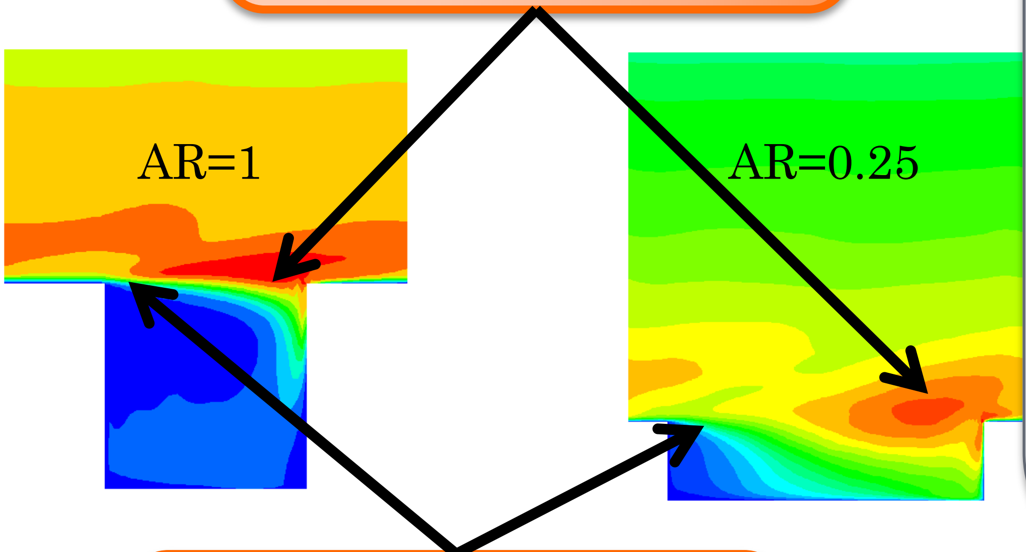
$$-\frac{1}{2}\left(u''w''\right)\times\left(\frac{\partial \bar{u}}{\partial z}+\frac{\partial \bar{w}}{\partial x}\right)$$

RESOLVED-SCALE TKE (AR=1)



RS-TKE CONTOURS

Maximum TKE



Maximum shear

Local turbulence production is not the major source of roof-level TKE for pollutant removal.

- Cui *et al.* (2004) found that sweeps ($u''>0$, $w''<0$) dominate the total momentum flux at roof level using LES with street canyon of AR=1.

- Christen *et al.* (2007, pp.1962) figured out that under neutral stratification, sweeps dominate the exchange of vertical momentum at $z \leq 2.5h$, employing quadrant analysis on the data measured from street canyons in Basel, Switzerland.

Section summary

- The re-circulating flows carry the pollutant to the roof level and also mix/dilute the pollutant within the street canyon.
- The aged air (carrying pollutant) is removed by ejections while fresh air is entrained by sweeps.
- The TKE required for pollutant removal is mainly attributed to the (downward moving) atmospheric turbulence in the UBL.

Results & Discussion

Pollutant dispersion in the UBL

NECESSARY DOMAIN SIZE

- In the LES of open-channel flows over a flat, smooth surface, the domain-length-to-domain-height ratio is often greater than 4π in order to resolve the turbulence correctly. (e.g. Enstad *et al.* 2006)

- Its computational cost is too high, if roughness are explicitly resolved.

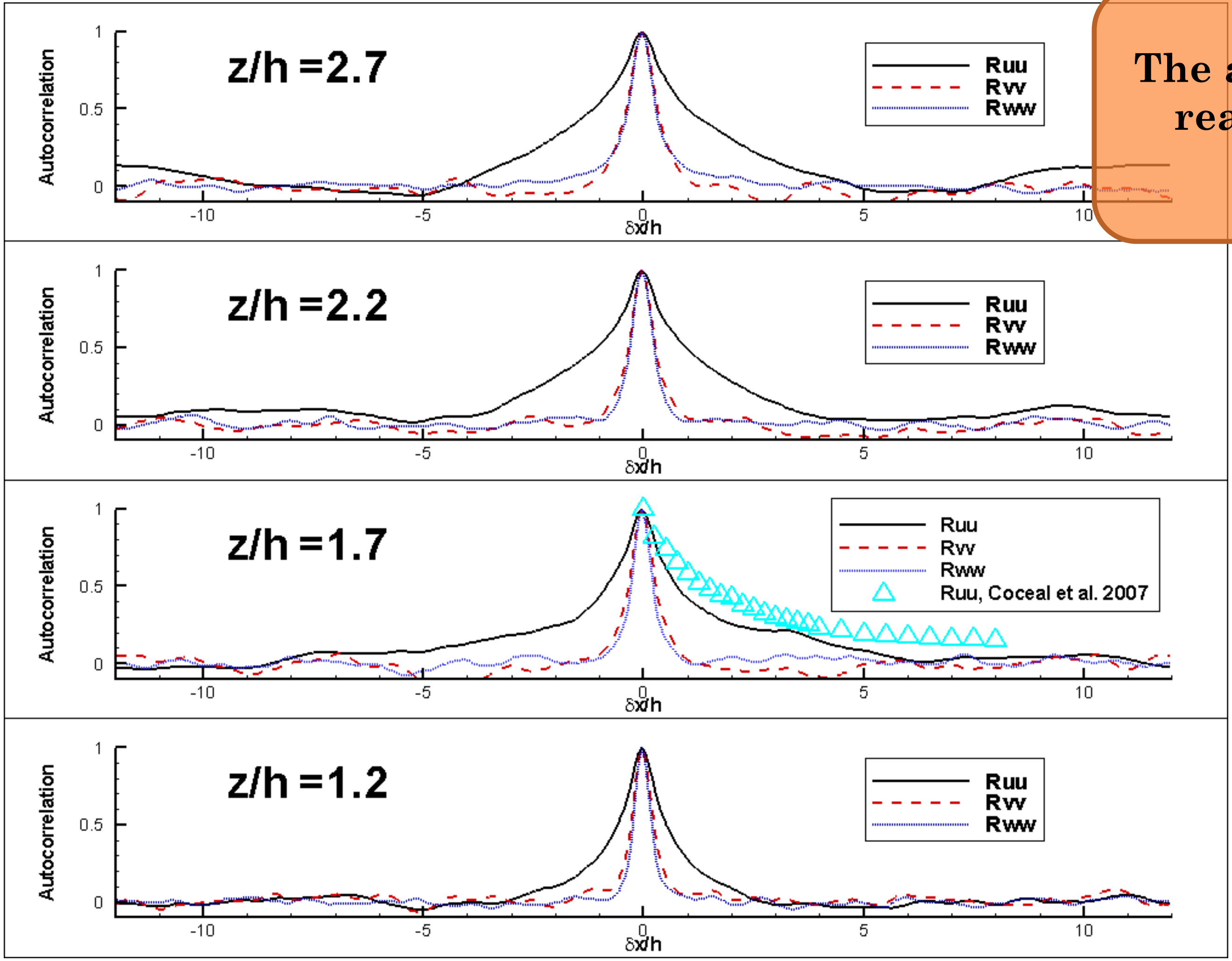
TWO-POINT CORRELATION

- Two-point correlations are commonly used to determine the necessary (minimum) domain size for resolving the turbulence. Ideally, the correlation of flow velocity drops to zero at certain horizontal separation, which is then used to determine the length scale of turbulence.

$$R_{uu} = \frac{\left\langle \bar{u}''(x_0)\bar{u}''(x_0 + \delta x) \right\rangle}{\sigma_{\bar{u}(x_0)}\sigma_{\bar{u}(x_0+\delta x)}}$$

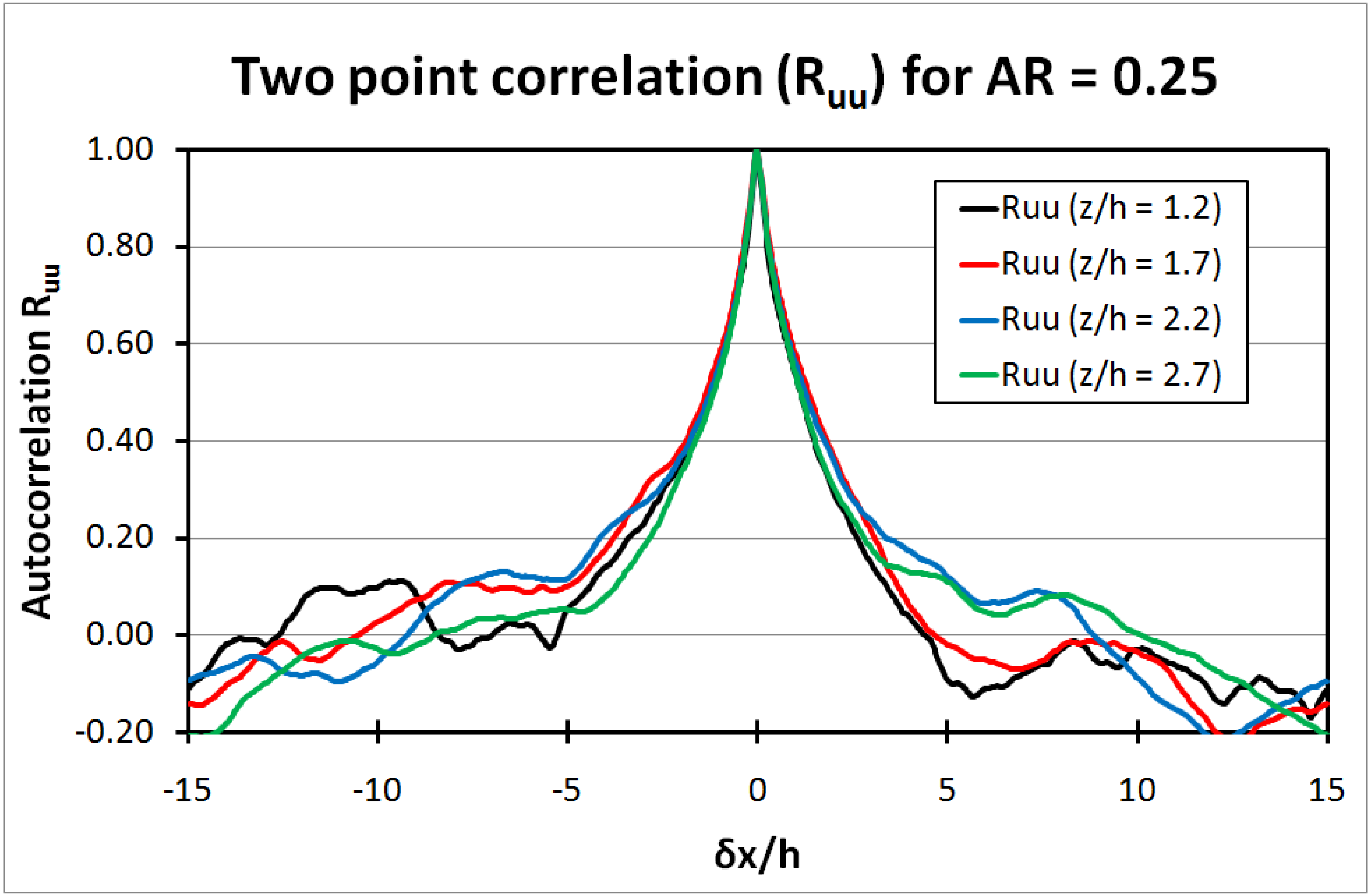
- where $u'' = u - \langle u \rangle_{y,t}$

TWO-POINT CORRELATION (AR =1)



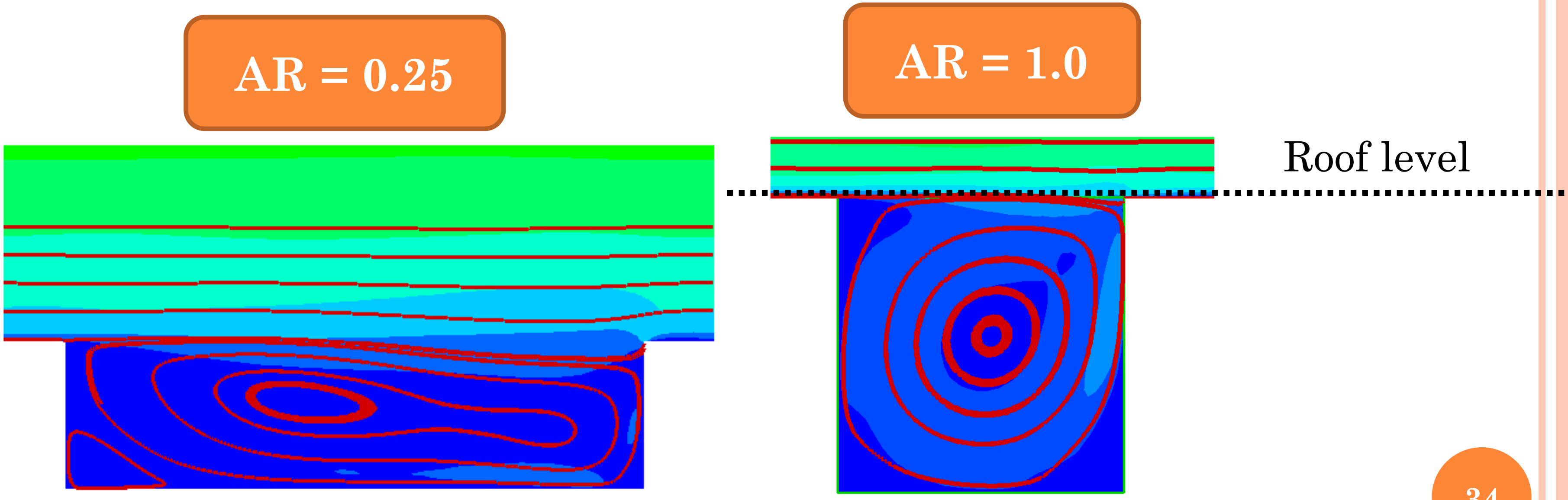
The autocorrelation reaches 0 at any elevations.

Two-point correlation (AR =0.25)

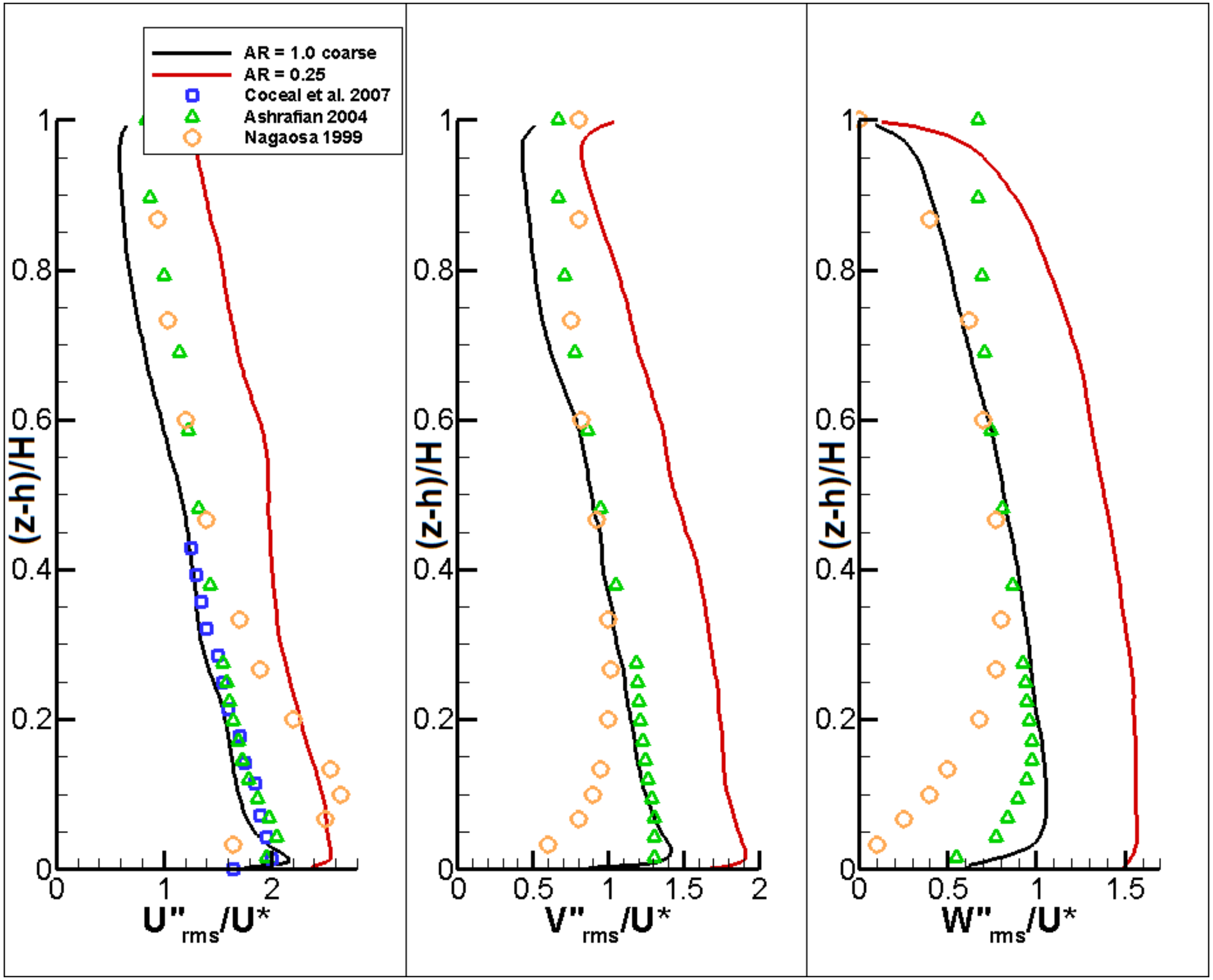


Streamlines

- The streamlines in the UBL are almost parallel to the streamwise direction.

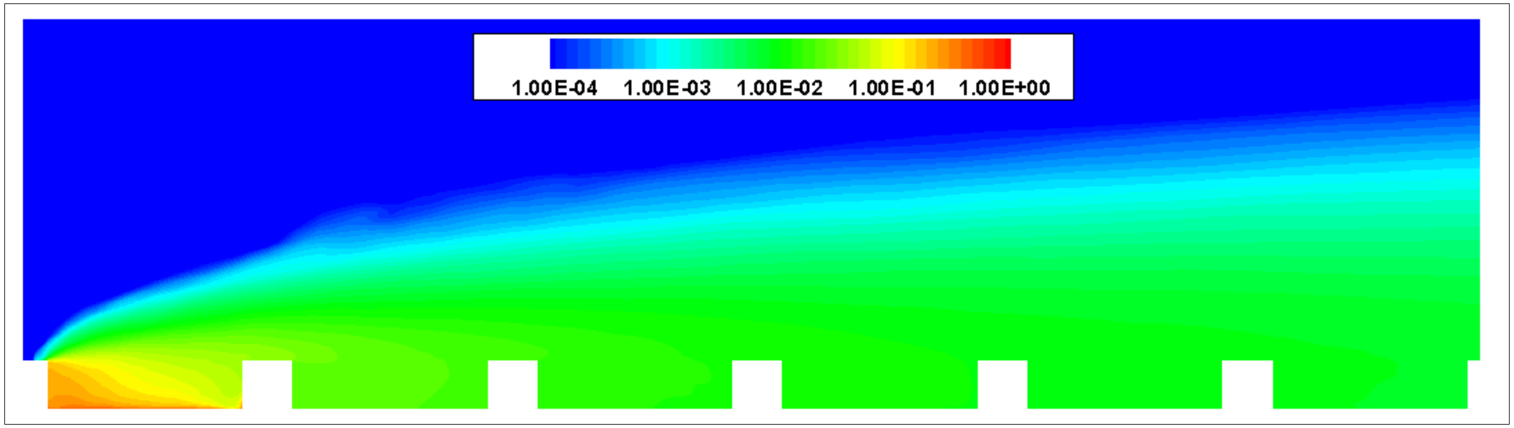


Flow fluctuation

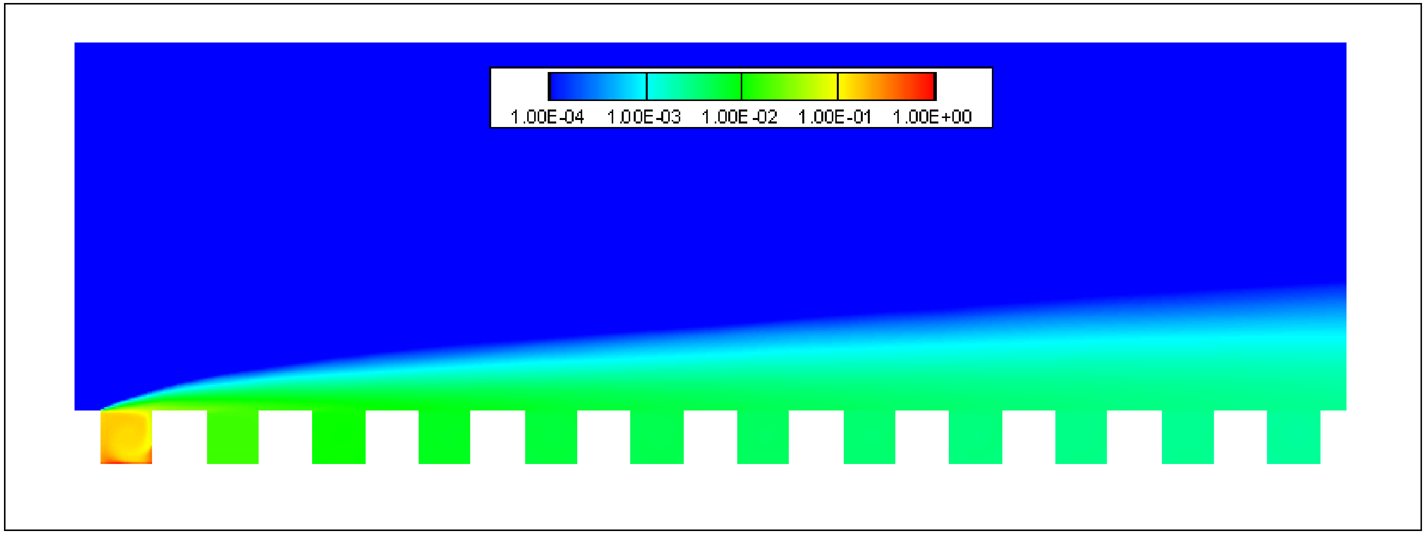


Pollutant plume

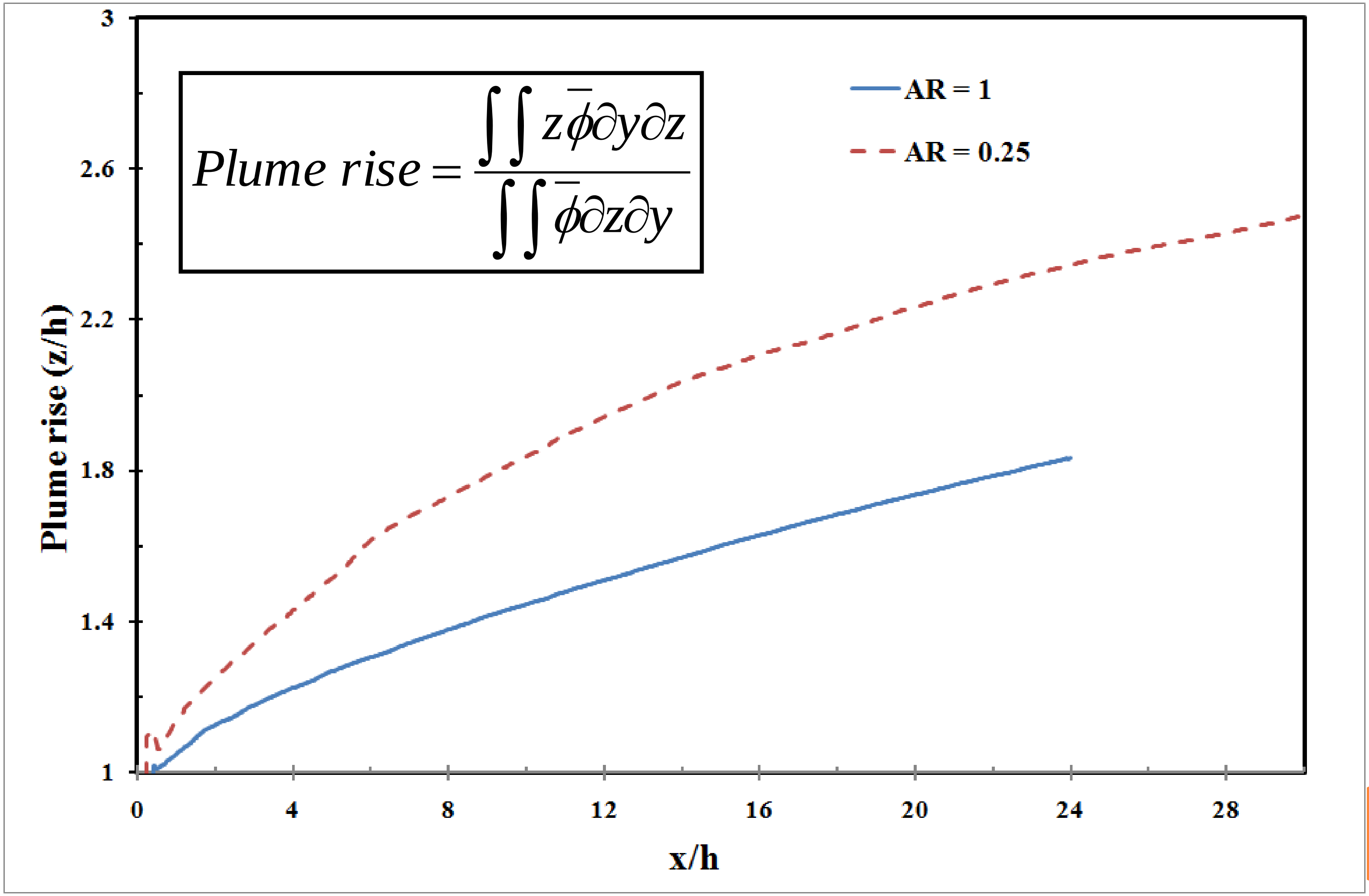
AR = 0.25



AR = 1

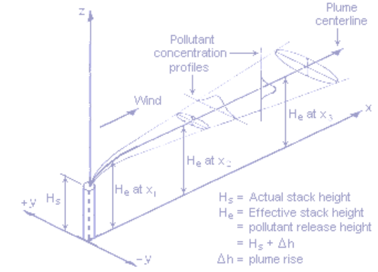


Plume rise



$$Plume\ rise = \frac{\iint z\bar{\phi}\,\partial y\,\partial z}{\iint \bar{\phi}\,\partial z\,\partial y}$$
AR = 1
AR = 0.25
Plume rise (z/h)
3
2.6
2.2
1.8
1.4
1
0
4
8
12
16
20
24
28
x/h

PLUME PROFILES

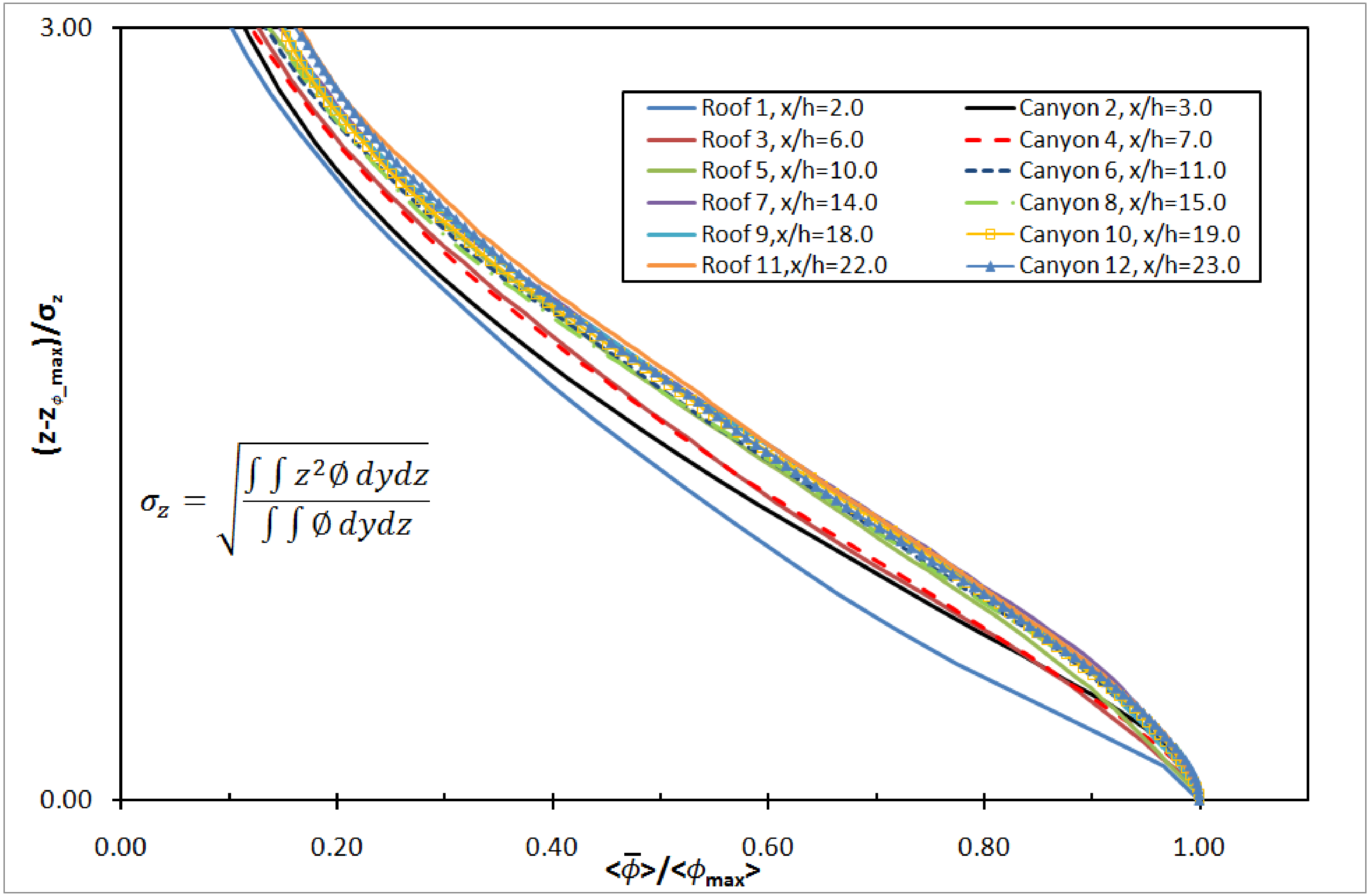


Extracted from:
http://www.thefullwiki.org/Air_pollution_dispersion_terminology

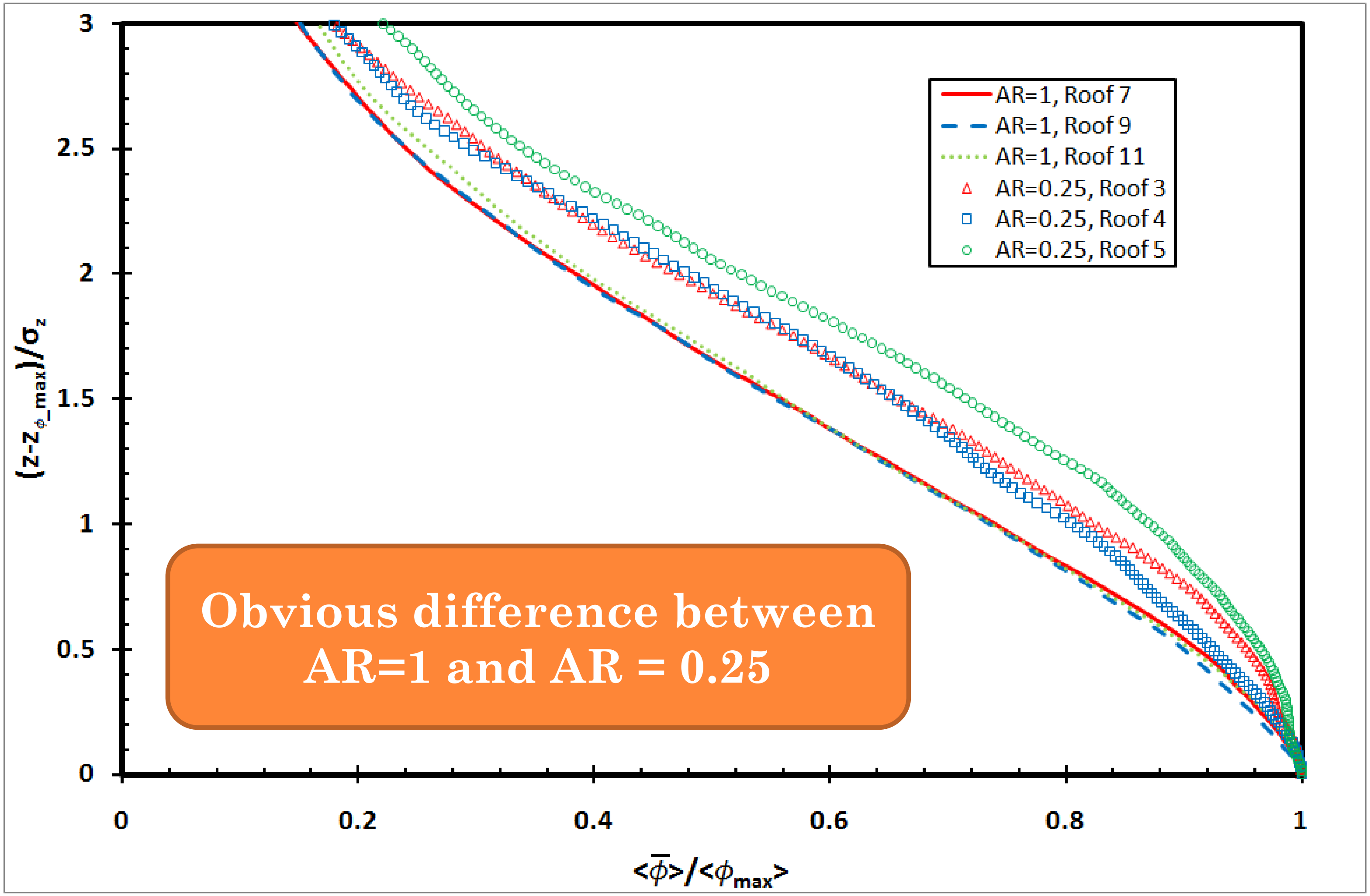
- Gaussian pollutant plume model has been widely used in the last 5 decades.
  - It was originally designed for rural areas (open terrain).
  - The re-circulating flows below the UBL are not considered

- Davidson *et al.* (1996), using wind tunnel experiments, showed that the pollutant plume over an obstacle array exhibits a Gaussian form.

Vertical Plume profile (AR=1)



Vertical Plume



Section summary

- The current computational domain is large enough handling the atmospheric turbulence in the UBL over idealized 2D urban roughness.
- The street canyons of AR = 0.25 would have better air quality compared with AR = 1 counterparts.
- The vertical plume profiles are functions of ARs.

ACKNOWLEDGMENT

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End

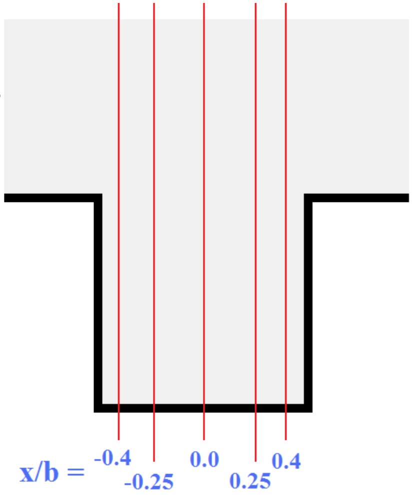
Q & A

Results & Discussions

Model validation

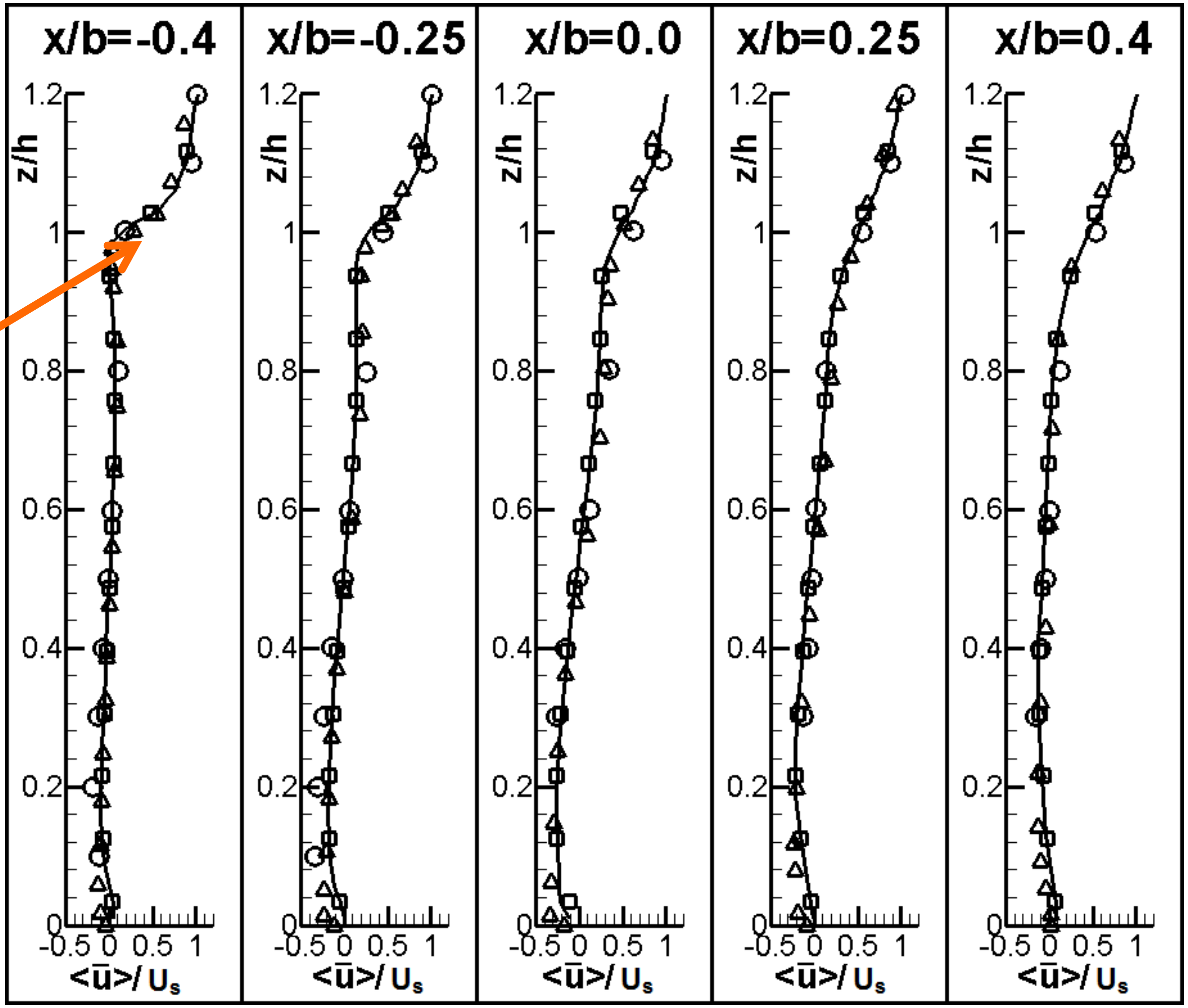
FLOW STRUCTURE WITHIN CANYON

- The vertical profiles of the following parameters on the vertical plane of the model with AR =1 were investigated:
  - Mean flow velocity, u and w
  - Turbulence Kinetic Energy, TKE
  - Skewness of u and w
  - Kurtosis of u and w



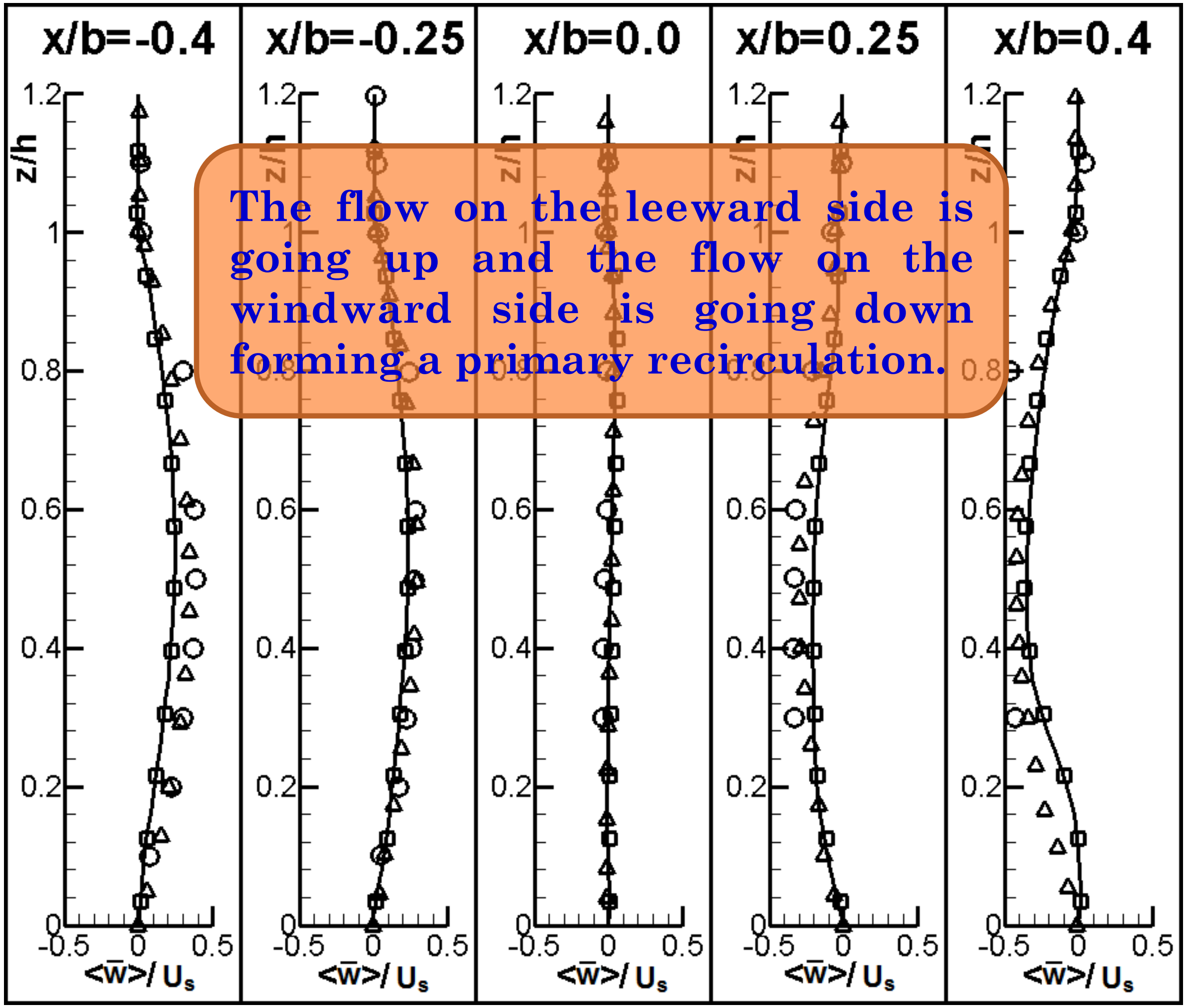
The results are compared with LES model by Cheng 2010 (represented by squares), Cui et al. 2004 (represented by triangles) & wind tunnel experiment by Brown 2000 (represented by circles).

Mean flow velocity, U



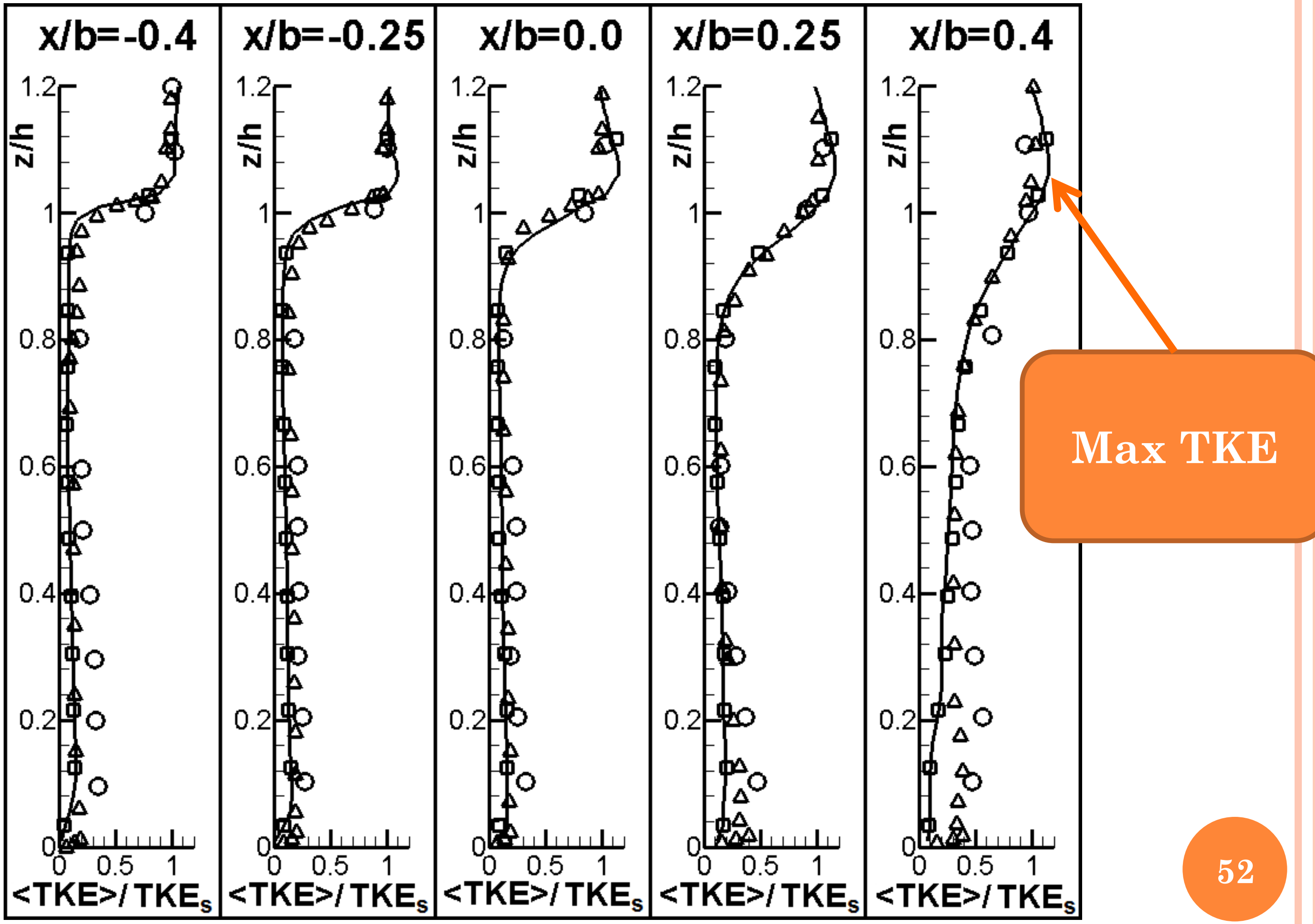
Max gradient

MEAN FLOW VELOCITY, W

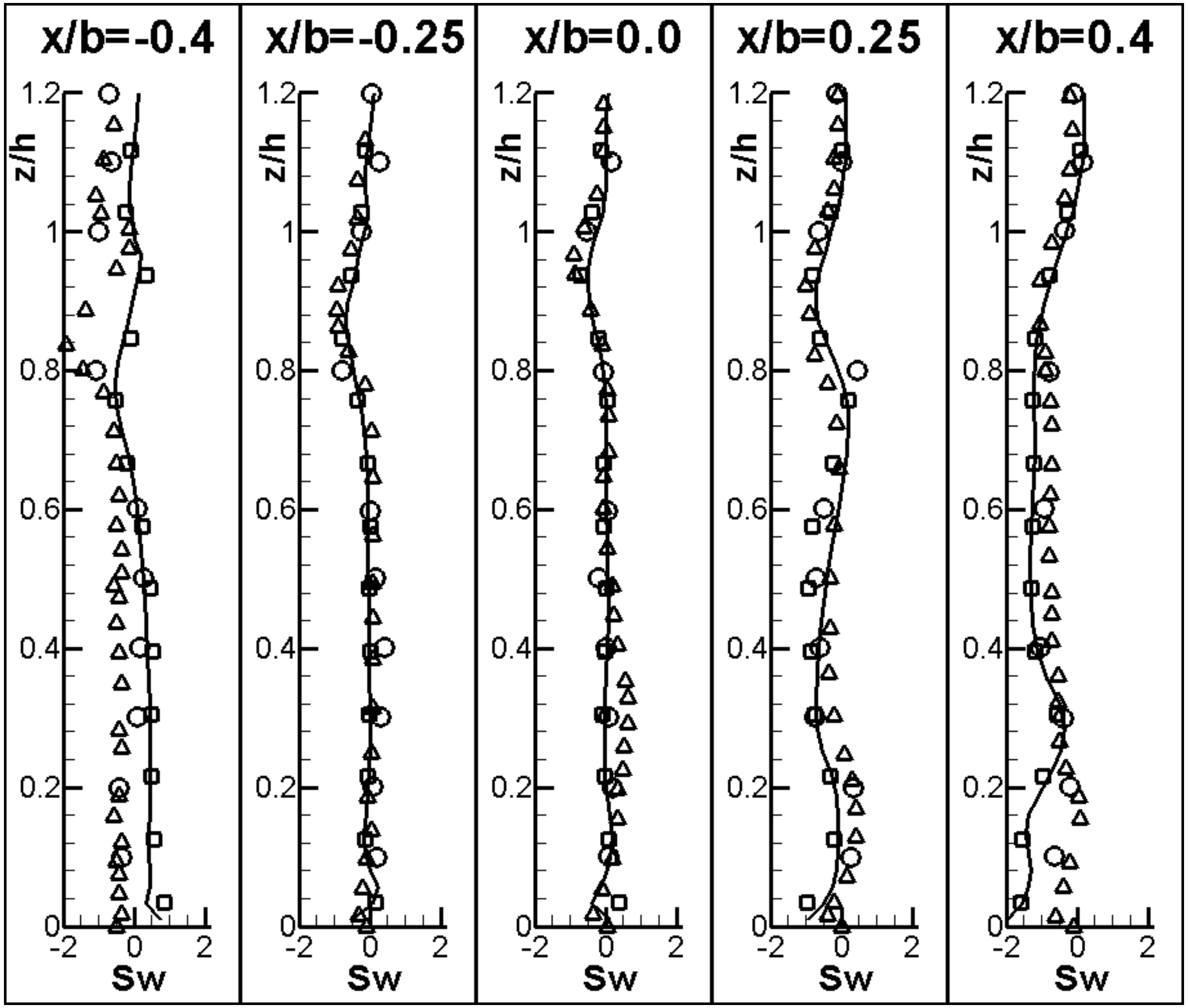


The flow on the leeward side is going up and the flow on the windward side is going down forming a primary recirculation.

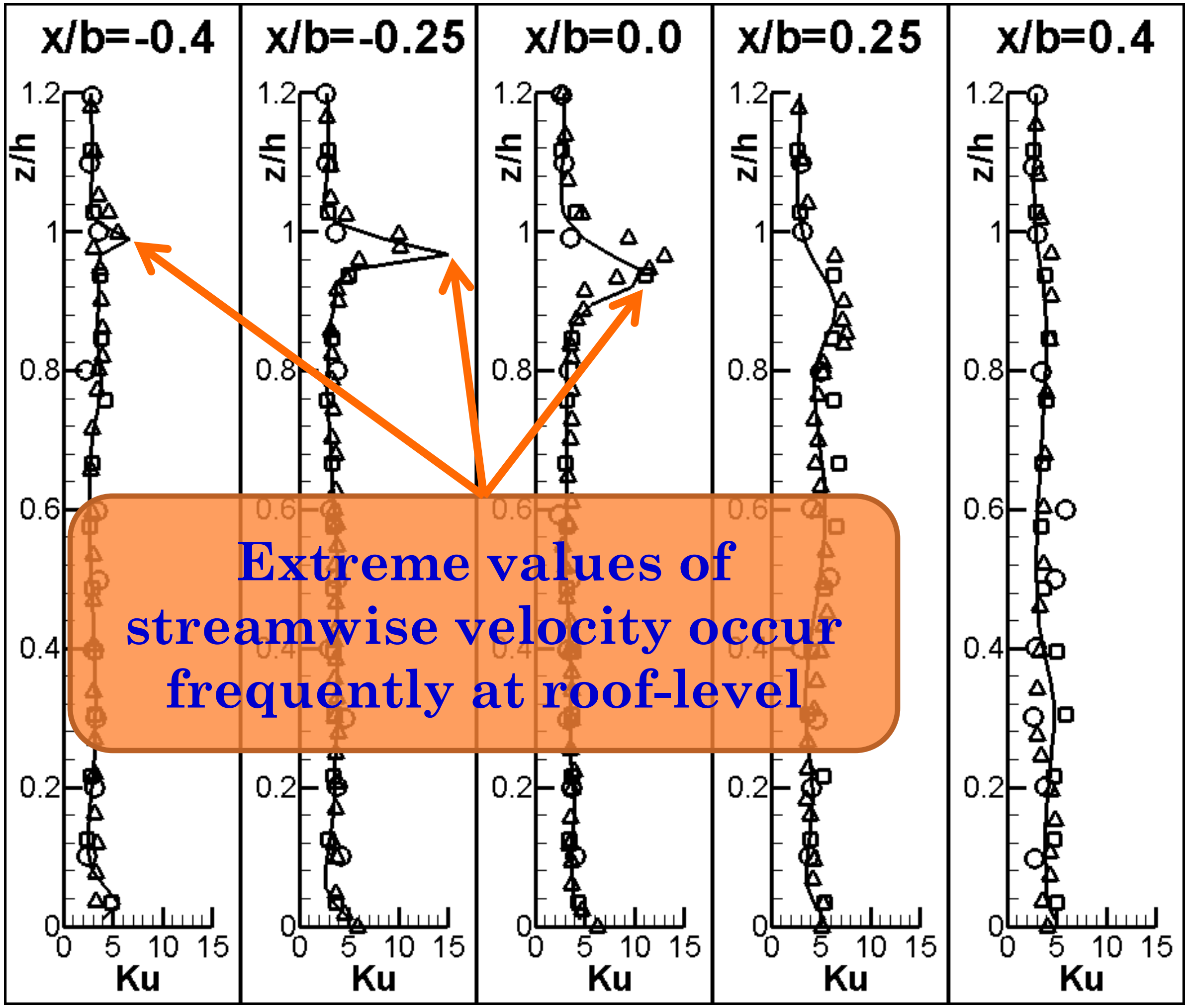
TKE



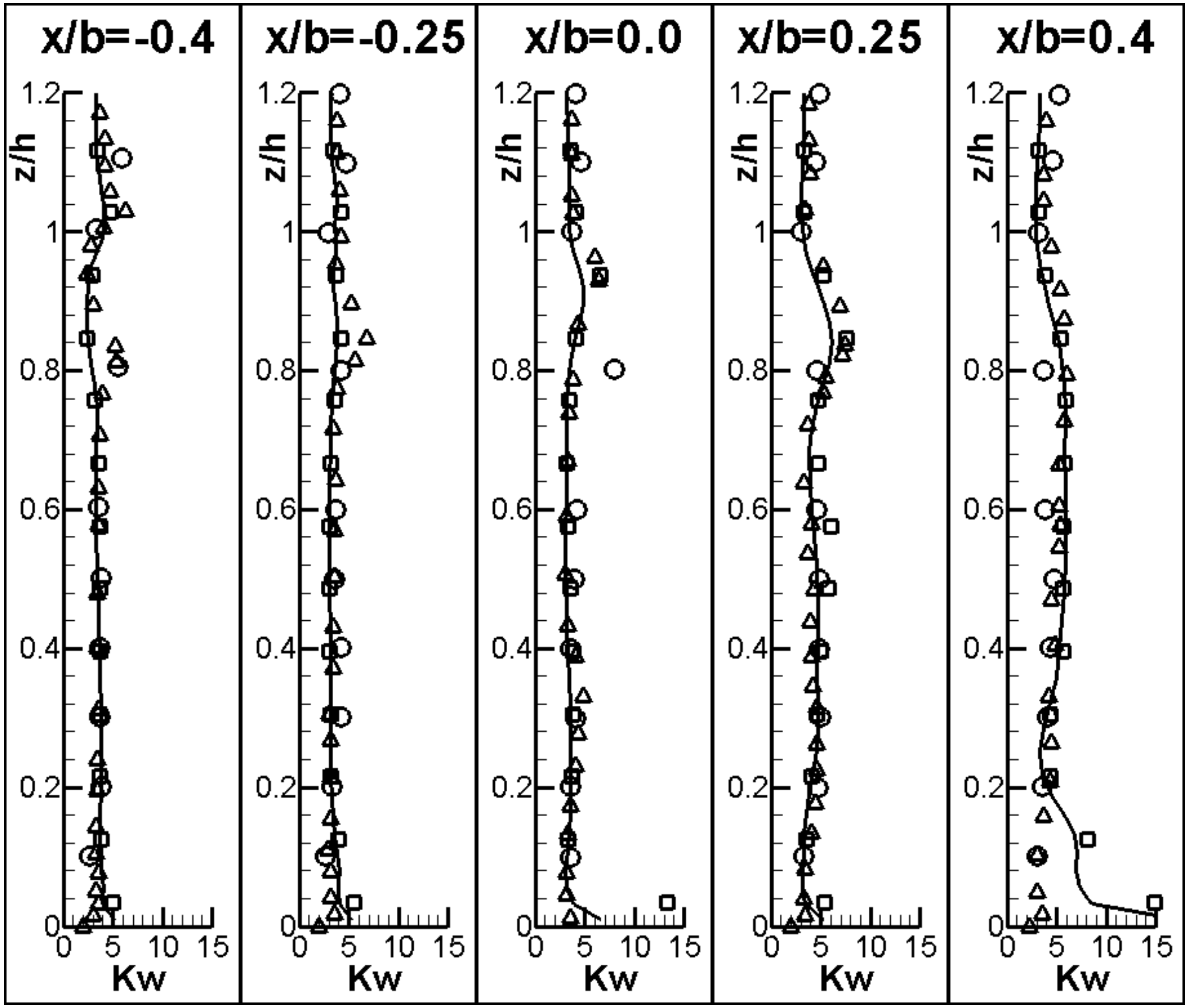
Skewness of w



Kurtosis of u



Kurtosis of w



Results & Discussions

Mathematic equations

NUMERIC METHOD

- Time derivative
  - Implicit second-order accurate backward differencing

- Spatial derivative (gradient, divergence, and laplacian terms)
  - Second-order accurate Gaussian finite volume integration scheme

- Interpolation scheme (cell surfaces' value)
  - Central differencing using values from cell center

Mathematical Equations

- Mass conservation equation:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

- Momentum conservation equation:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j = -\Delta P \delta_{i,1} - \frac{1}{\rho}\frac{\partial \overline{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_i x_j}$$

  - Resolved scale modified pressure

$$\overline{\pi} = \overline{p} + \frac{2}{3}k_{SGS}$$

MATHEMATICAL EQUATIONS

- The SGS Reynolds stresses (Smagorinsky, 1963)

$$-\tau_{ij} = -(\overline{u_i u_j} - \bar{u}_i \bar{u}_j) = \nu_{SGS}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_i}{\partial x_i}\right) + \frac{2}{3} k_{SGS} \delta_{ij}$$

- SGS turbulence viscosity

$$\nu_{SGS} = C_k k_{SGS}^{1/2} \Delta$$

- filter width $\Delta = \left[\Delta_1 \Delta_2 \Delta_3\right]^{1/3}$

- modeling constant $C_k = 0.07$

Mathematical Equations

- One-equation SGS model (Schumann, 1975)

$$\frac{\partial k_{SGS}}{\partial t}+\frac{\partial}{\partial x_j}\bar{u}_i k_{SGS}=-\frac{1}{2}\tau_{ij}\frac{\partial \bar{u}_i}{\partial x_j}+\left(\nu+\nu_{SGS}\right)\frac{\partial^2 k_{SGS}}{\partial x_i x_j}-C_\varepsilon\frac{k_{SGS}}{\Delta}$$

  - modeling constant $C_\varepsilon = 1.05$

Mathematical Equations

- Scalar transport equation

$$\frac{\partial \overline{\phi}}{\partial t} + \frac{\partial}{\partial x_j} \overline{u}_i \overline{\phi} = \frac{\partial \gamma_i}{\partial x_i} + \frac{\nu}{Sc} \frac{\partial^2 \overline{\phi}}{\partial x_i x_j}$$

  - Schmidt number

$$Sc = 0.72$$

  - SGS pollutant flux

$$\gamma_i = \overline{\phi u_i} - \overline{\phi}\overline{u}_i = -\frac{\nu_{SGS}}{Sc} \frac{\partial \overline{\phi}}{\partial x_i}$$