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Large-eddy simulation of wind flows and pollutant transport inside and over idealized urban street canyons in unstable thermal stratification

Ming-Chung Chan & Chun-Ho Liu*

Department of Mechanical Engineering, The University of Hong Kong
Pokfulam Road, Hong Kong, China

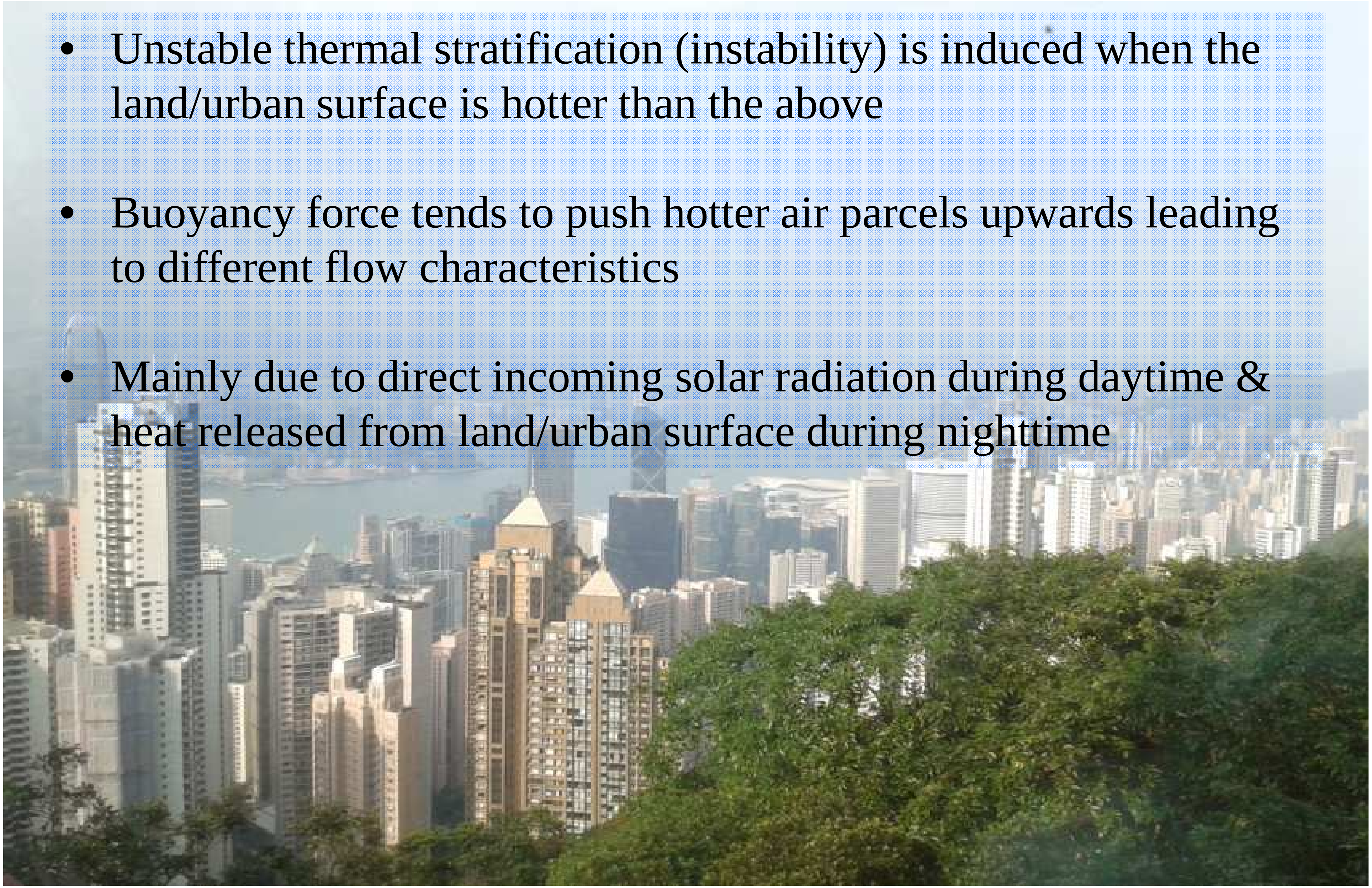
**Corresponding Author*: Dr. Chun-Ho LIU; Department of Mechanical Engineering, 7/F Haking Wong Building, The University of Hong Kong, Pokfulam Road, Hong Kong, CHINA; *Tel*: (852) 2859 7901; *Fax*: (852) 2858 5415; liuchunho@graduate.hku.hk

Table of Contents

- Introduction
- Highlights of previous studies
- Objectives
- Methodology
- Comparison between LES & wind tunnel results
- Findings & discussion
- Conclusions

Introduction

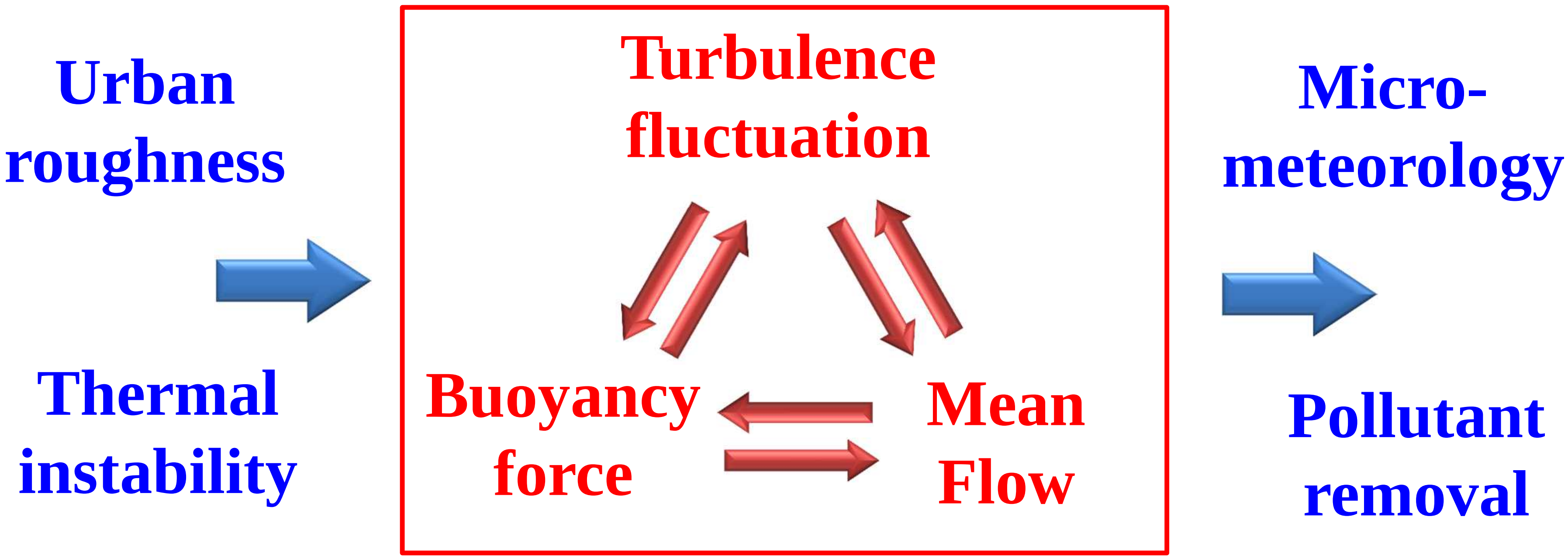
- Unstable thermal stratification (instability) is induced when the land/urban surface is hotter than the above
- Buoyancy force tends to push hotter air parcels upwards leading to different flow characteristics
- Mainly due to direct incoming solar radiation during daytime & heat released from land/urban surface during nighttime



Photography taken at Noon, - The Peak, Hong Kong

Motivations

- Some previous studies showed that unstable stratification tends to promote pollutant dispersion & turbulent mixing, which in turn improves the street canyon air ventilation



Motivations

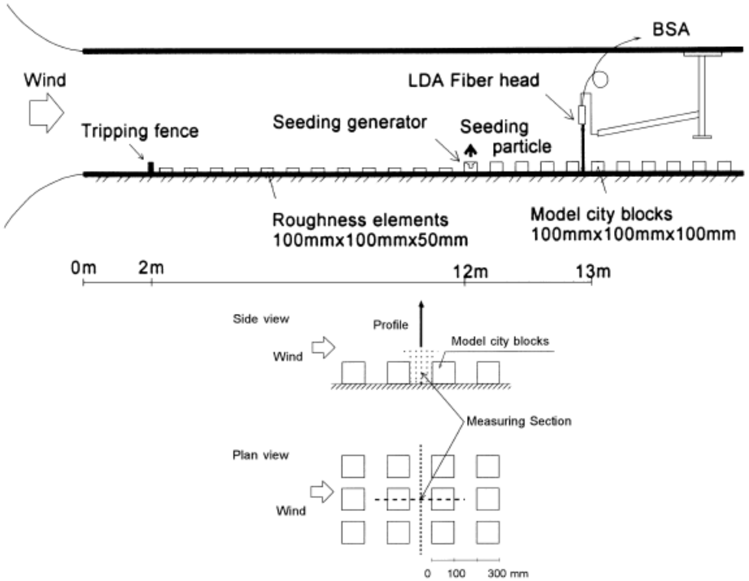
- Urban morphology is characterized by large roughness height which enhances turbulent generation

- High heat capacity of urban surface & trapping of thermal energy inside street canyons increase the duration of unstable stratification, compared with that over rural terrain
  - e.g. observation showed 85% in daytime & 64% at nighttime (Niachou et al. 2008)

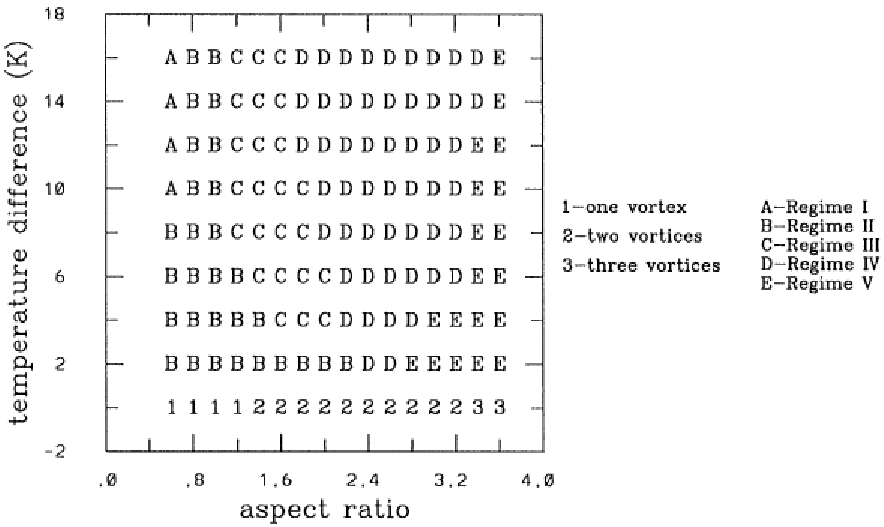
- It is advantageous to understand the characteristics of flows & pollutant dispersion under unstable stratification in urban areas

- However, those researches are limited in the literature

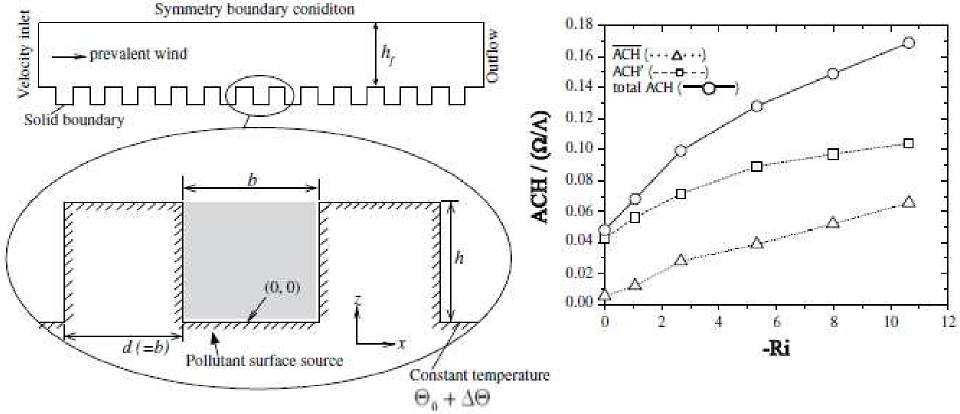
Highlights of previous studies

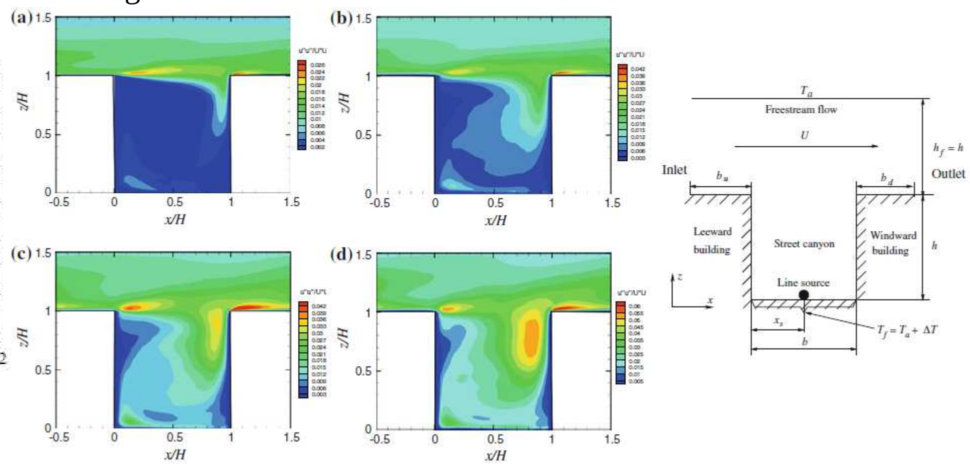


Uehara et al. (2000) – Wind tunnel experiments on how thermal stratification affects flows in and above urban street canyons



Kim and Baik (2001) – Urban street-canyon flows with bottom heating





Cheng et al.(2009) – On the correlation of air and pollutant exchange for street canyons in combined wind-buoyancy-driven flow

Li et al. (2010) – Large-eddy simulation of flow and pollutant transport in urban street canyons with ground heating

Objectives

Since the micro-meteorology and pollutant removal of street canyons strongly depend on the flow conditions just above the urban roughness, this presentation mainly focuses on

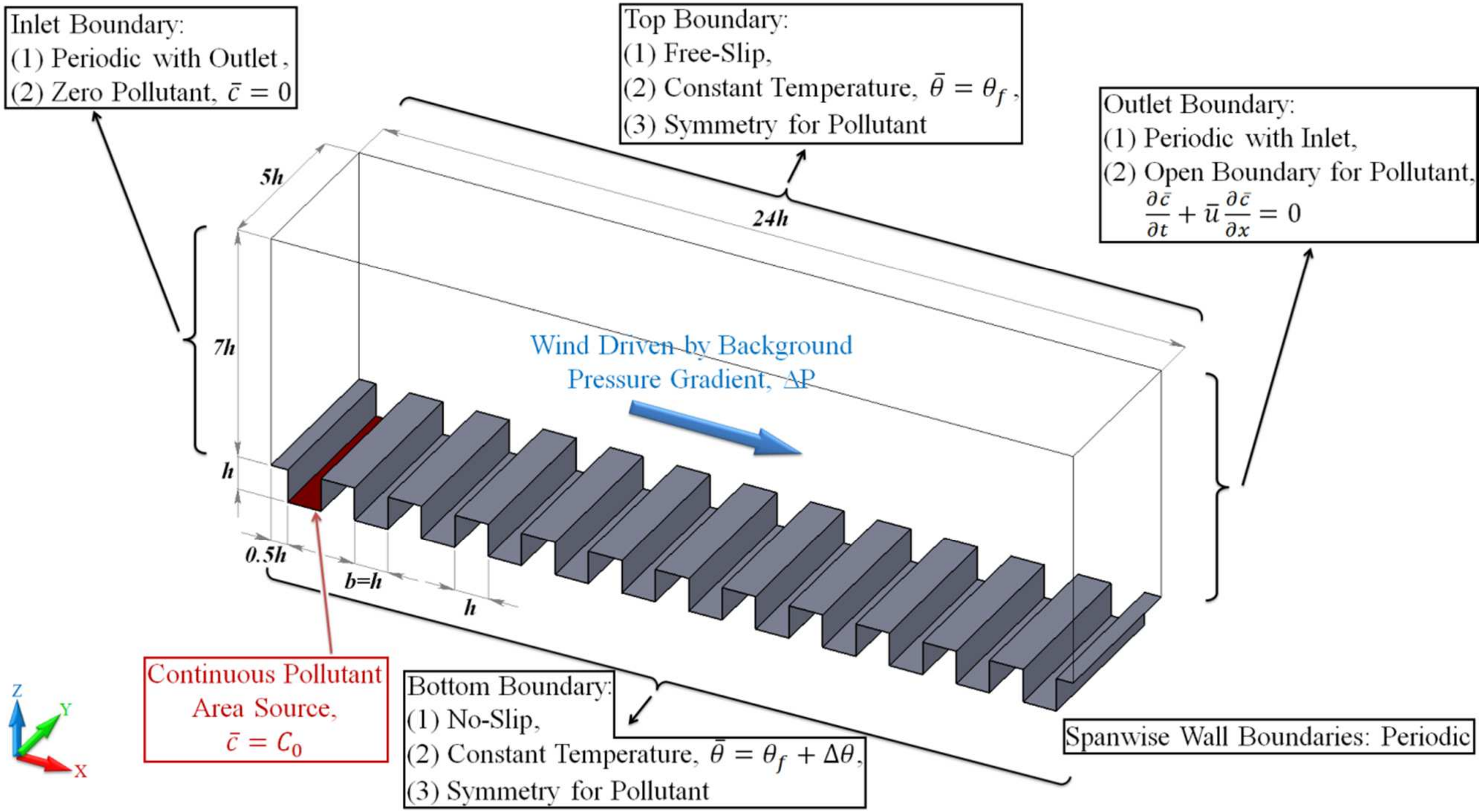
1) the wind flows (mean wind & turbulent statistics),
2) the logarithmic mean wind profiles, and
3) the pollutant dispersion characteristics above urban surface

under different intensities of (slightly) unstable stratification

This study is performed in a fundamental way by using idealized urban geometries & background conditions, & using LES to resolve all the large-scale turbulence explicitly

Methodology

- Large-eddy simulation (**LES**) with one-equation subgrid-scale (**SGS**) turbulence model (incompressible flow)
- By the open-source CFD code – **OpenFOAM**, version 2.1.0



Methodology

- Free-stream wind is driven by background pressure gradient ΔP (constant for all models)
- Buoyancy force is modeled by the Boussinesq approximation & is controlled by the gravitational acceleration g
- Solving the filtered governing equations for the resolved-scale flow vector, temperature & pollutant concentration

Background Pressure Gradient — Buoyancy Force

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\bar{u}_i\bar{u}_j = \boxed{\Delta P \delta_{i1}} - \frac{\partial \bar{p}}{\partial x_i} + (\nu + \nu_{SGS})\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \boxed{\alpha g(\bar{\theta} - \theta_0)\delta_{i3}}$$

Methodology

- Analyzing the pseudo steady-state properties
- Ensemble averaging in the temporal & spanwise domains that denoted by $<\phi>$
- Simulation conditions:

AR	Re_τ	Re_H	Ri_τ	Ri_H
1	4140	89,000 ↓ 42,000	0 ↓ -400	0 ↓ -3.92

By force balance in free-stream domain,

$$\tau_w = \rho \cdot \Delta P \cdot H$$

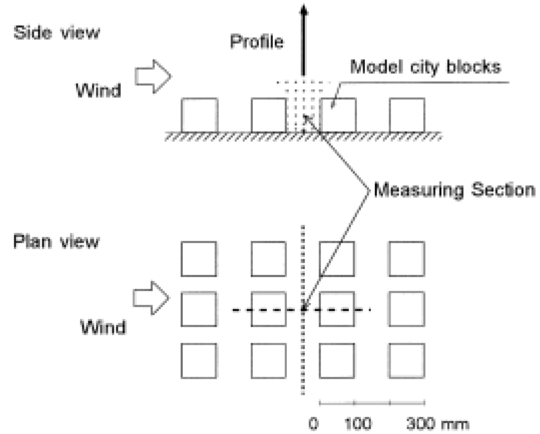
$$u_\tau = \sqrt{\tau_w/\rho} = \sqrt{\Delta P \cdot H}$$

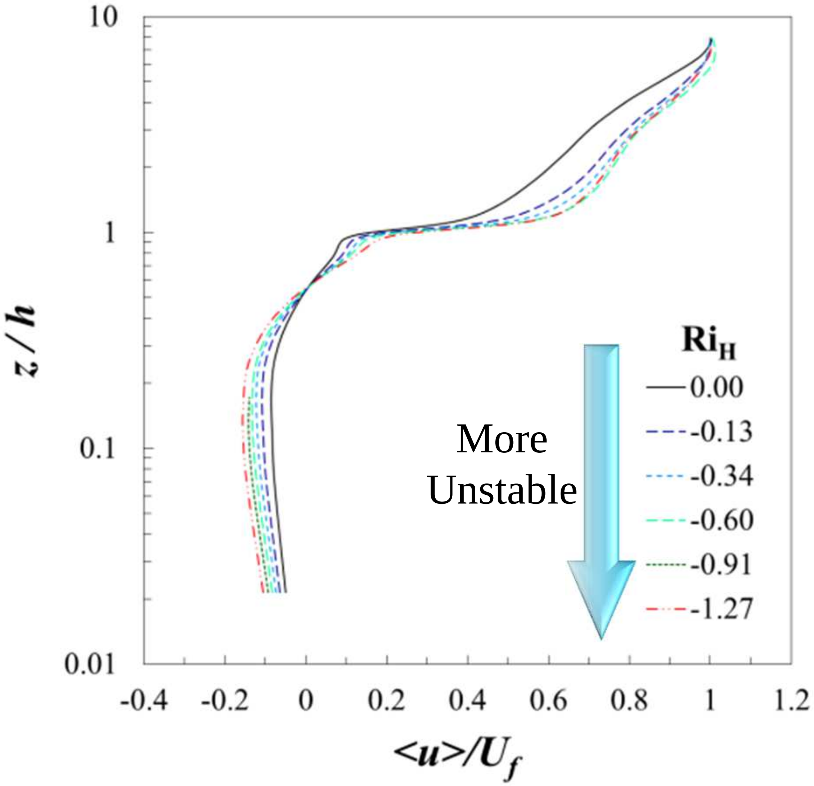
$$Re_H = \frac{H \cdot U_f}{\nu} \quad Ri_H = -\frac{\alpha g H \Delta\theta}{{U_f}^2}$$

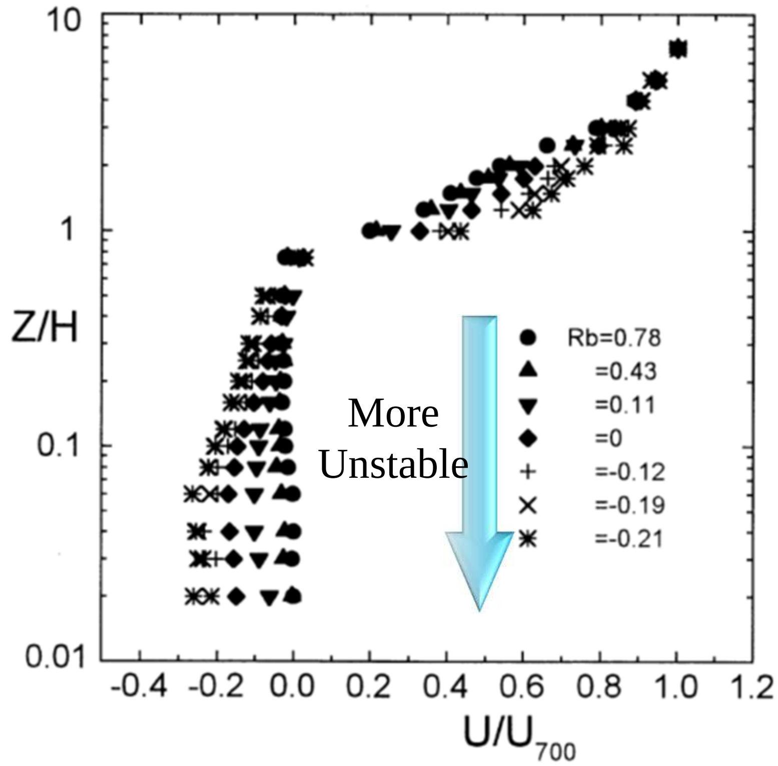
$$Re_\tau = \frac{H \cdot u_\tau}{\nu} \quad Ri_\tau = -\frac{\alpha g H \Delta\theta}{{u_\tau}^2}$$

Comparison between LES & wind tunnel models

- LES results show trends which are similar to the tunnel results by Uehara et al. (2000):
  - Wind flow relative to free-stream is enhanced both inside and above street canyon

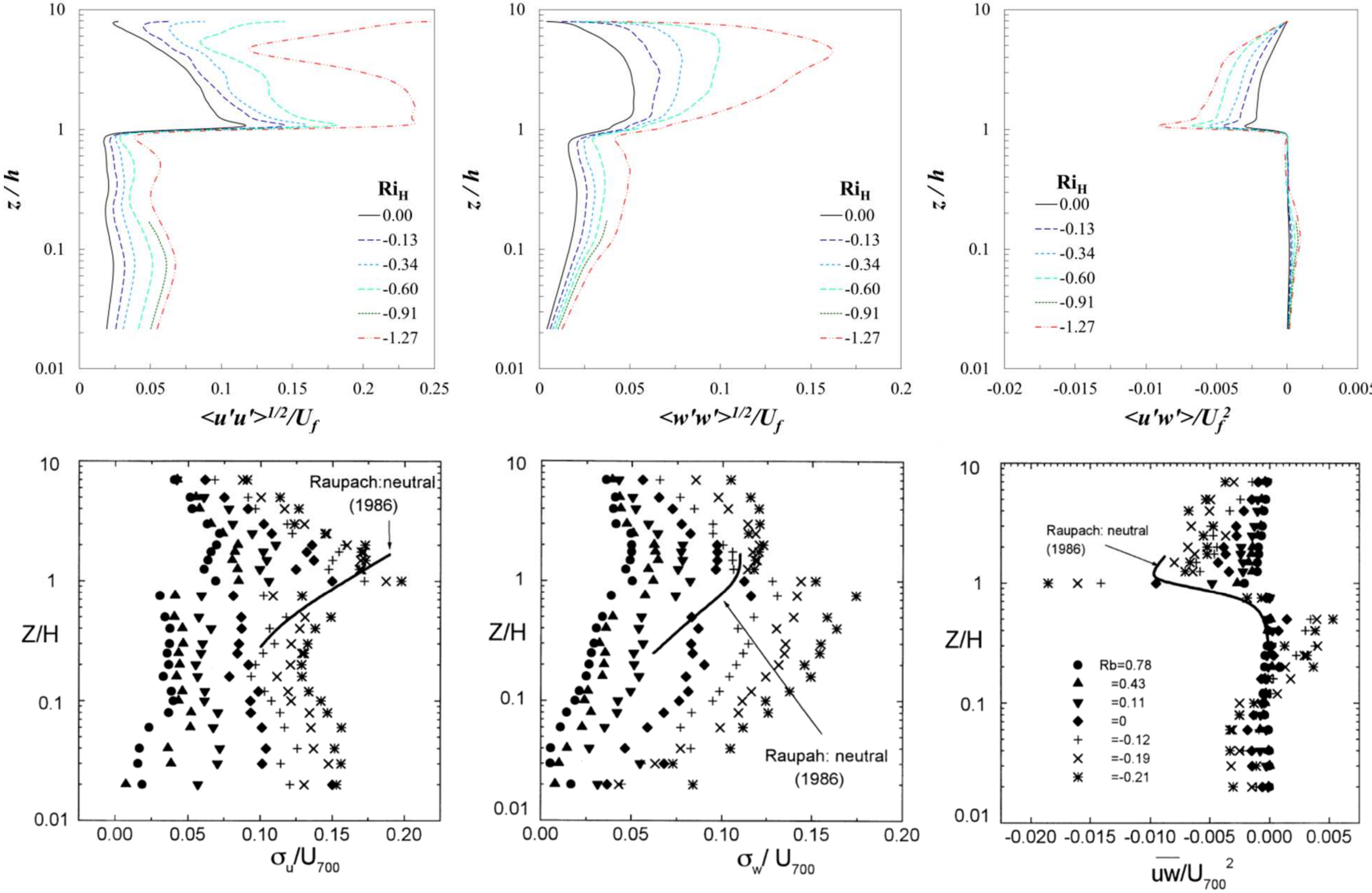






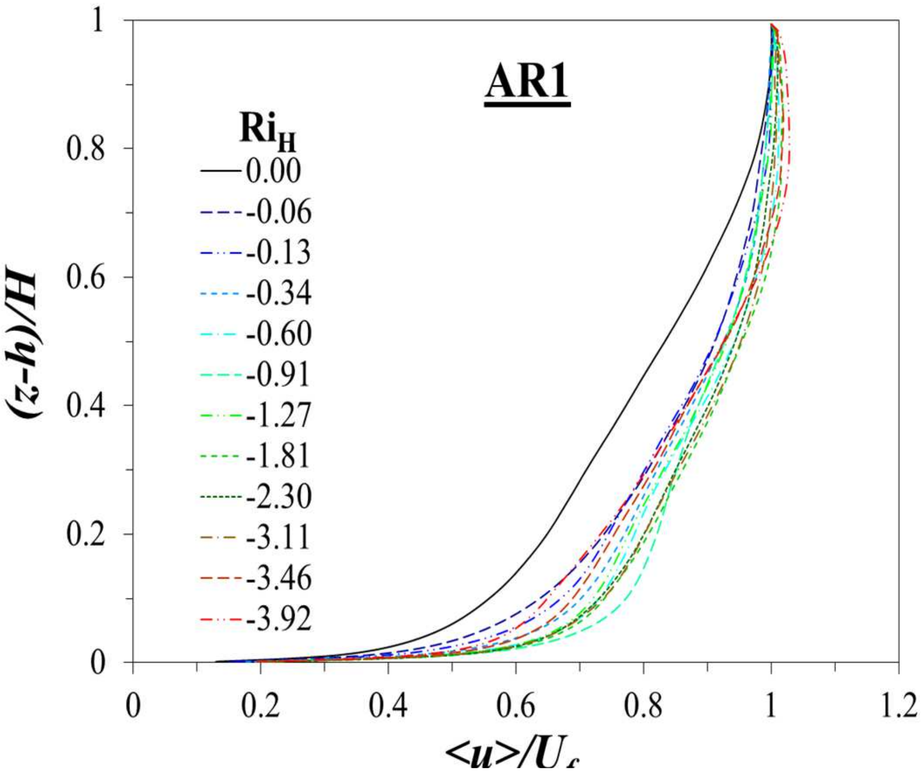
Comparison between LES & wind tunnel models

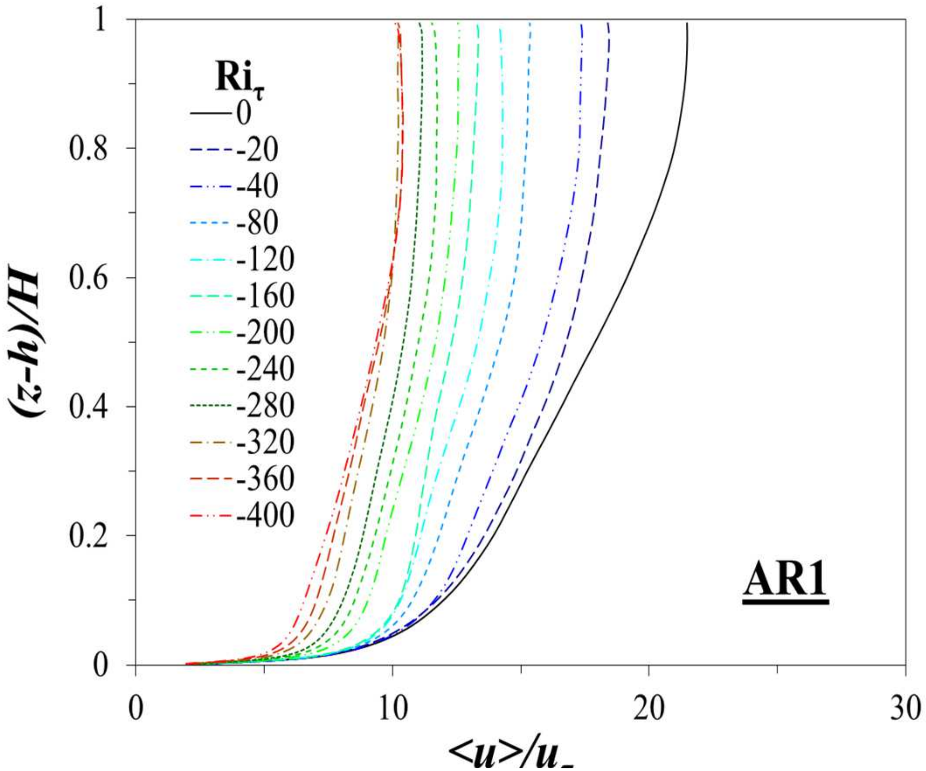
- Smaller magnitudes for wind fluctuations is observed since 2D geometry (ribs) is used in LES but 3D geometry is used in wind tunnel



Mean flow above urban roughness

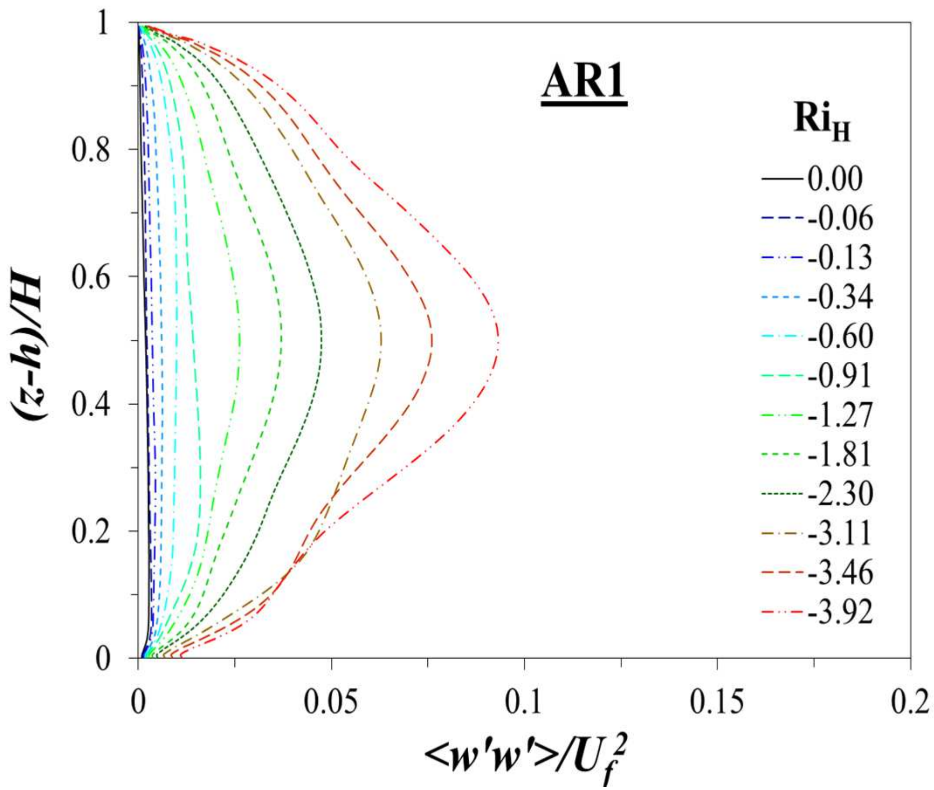
- The mean flow is further averaged in streamwise direction
- When instability increases, gradient of mean wind profile near roughness elements increases & it is more uniform above
- With constant driving force (constant u_τ), mean wind reduces with instability

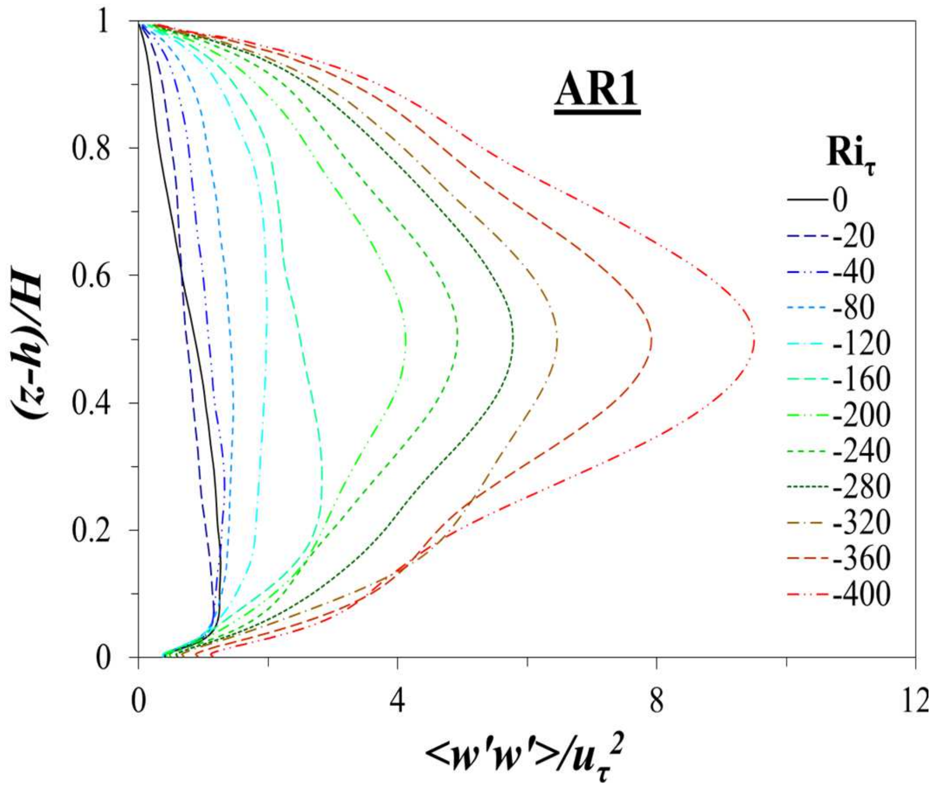




Wind fluctuation above urban roughness

- When instability increases, wind fluctuation increases that implies enhanced turbulent mixing
- The local maximum point of fluctuation shifts upwards as instability increases





Logarithmic law of the wall

Smooth surface

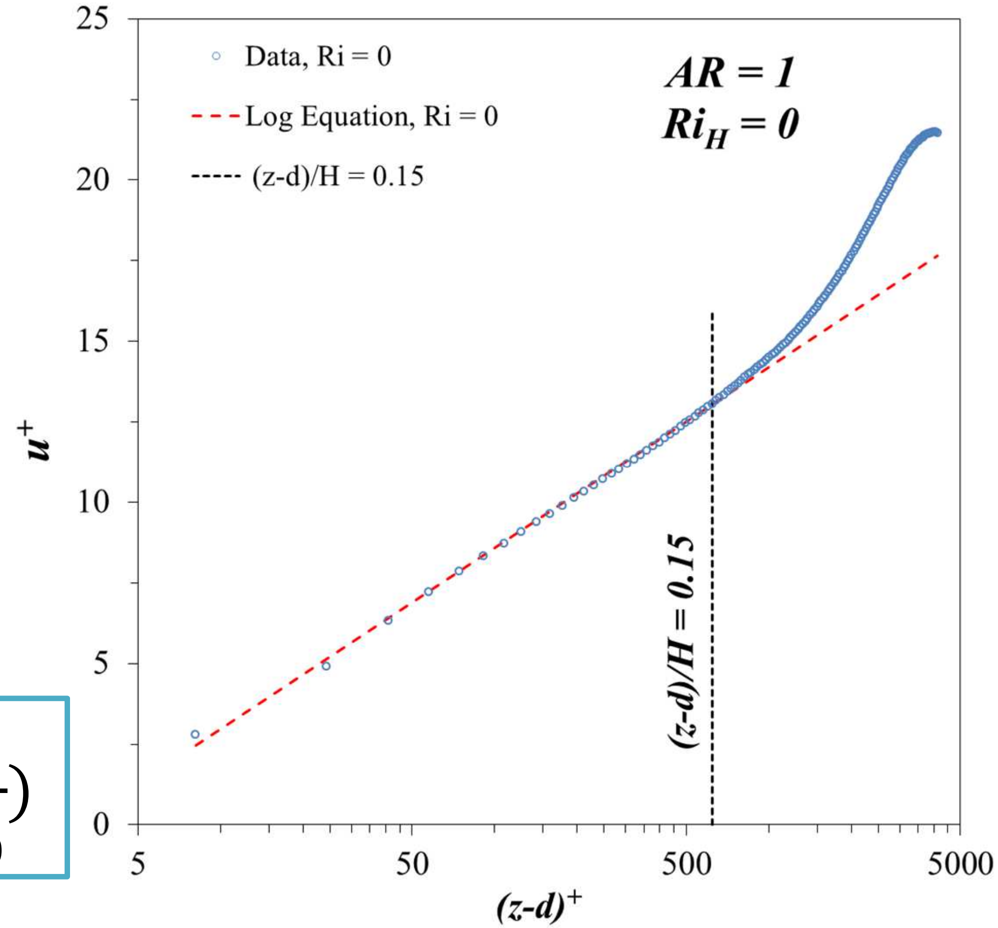
(by dimensional analysis):

$$\frac{du^+}{dz} = \frac{1}{z}\phi\left(\frac{z}{\delta_\nu}, \frac{z}{\delta}, \frac{z}{L}\right)$$

Neutral stratification:

($z/\delta_\nu >> 1$, $z/\delta << 1$ & $z/L \sim 0$)

$$\frac{du^+}{dz} = \frac{1}{\kappa z} \Rightarrow u^+ = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right)$$



Rough surface:

$$u^+ = \frac{1}{\kappa}\ln\left(\frac{z-d}{z_0}\right)$$

where

$\boldsymbol{u^+} = \frac{<u>}{u_\tau}$ & $\boldsymbol{\delta_\nu} = \frac{\nu}{u_\tau}$

u_τ: friction velocity
δ_ν: viscous length scale
δ: boundary layer/channel height
L: Monin-Obukov length scale
κ: von Kármán constant (~0.41)
d: displacement height

Logarithmic law of the wall

Unstable stratification ($L < 0$):

$$\frac{du^+}{dz} = \frac{1}{\kappa z}\phi_M\left(\frac{z}{L}\right)$$

Expanding ϕ_M by Taylor's series and neglecting higher orders:

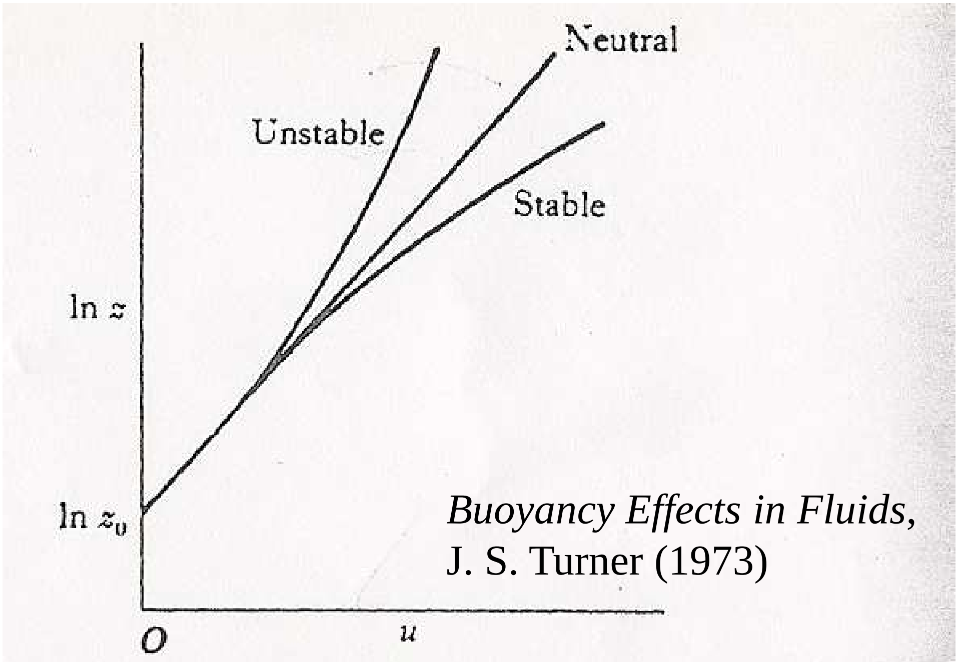
$$\frac{du^+}{dz} = \frac{1}{\kappa z}\left[1 + \alpha\left(\frac{z}{L}\right)\right]$$

$$u^+ = \frac{1}{\kappa}\left[\ln\frac{z}{z_0} + \alpha\frac{z}{L}\right]$$

for $z/L \ll 1$

Rough surface:

$$u^+ = \frac{1}{\kappa}\left[\ln\frac{z-d}{z_0} + \alpha\frac{z-d}{L}\right]$$



Buoyancy Effects in Fluids, J. S. Turner (1973)

The effect of a stable or unstable environment on turbulent velocity profiles.

where α is an empirical constant (~ 4.5 by Webb, 1970)

Monin-Obukov length:

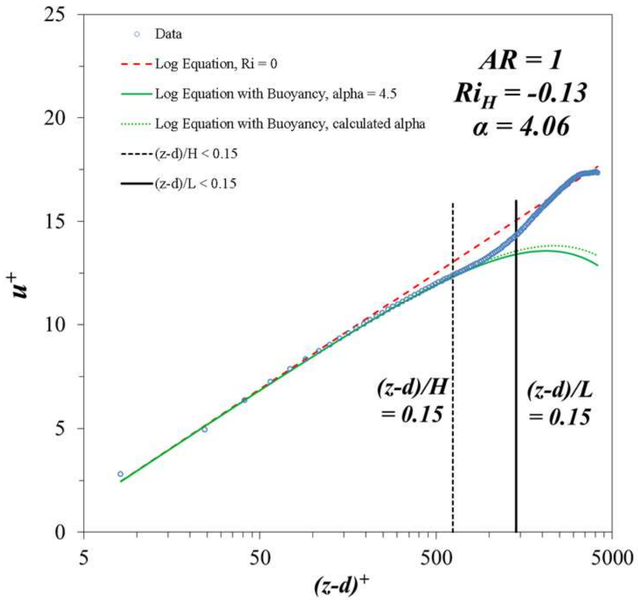
$$L = \frac{-u_\tau^3}{\kappa B}$$

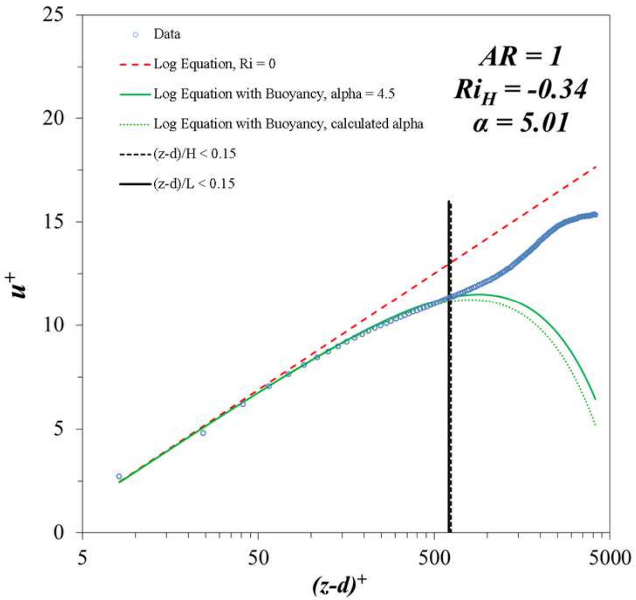
Buoyancy flux:

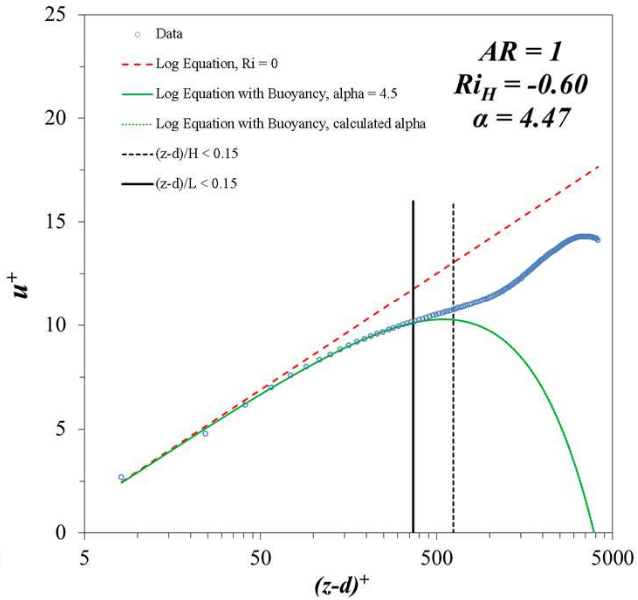
$$B = \frac{g}{\theta}\cdot\overline{\theta' w'}$$

Logarithmic law of the wall

- For slightly unstable cases, mean wind profiles are well described by the log-law equation
- Decrease in wind speed is due to the increased drag by (enhanced) turbulent mixing
- Empirical constant α is calculated by the linear regression for small z/L (using data for z/L<0.15) that is found to be ~ 4.5

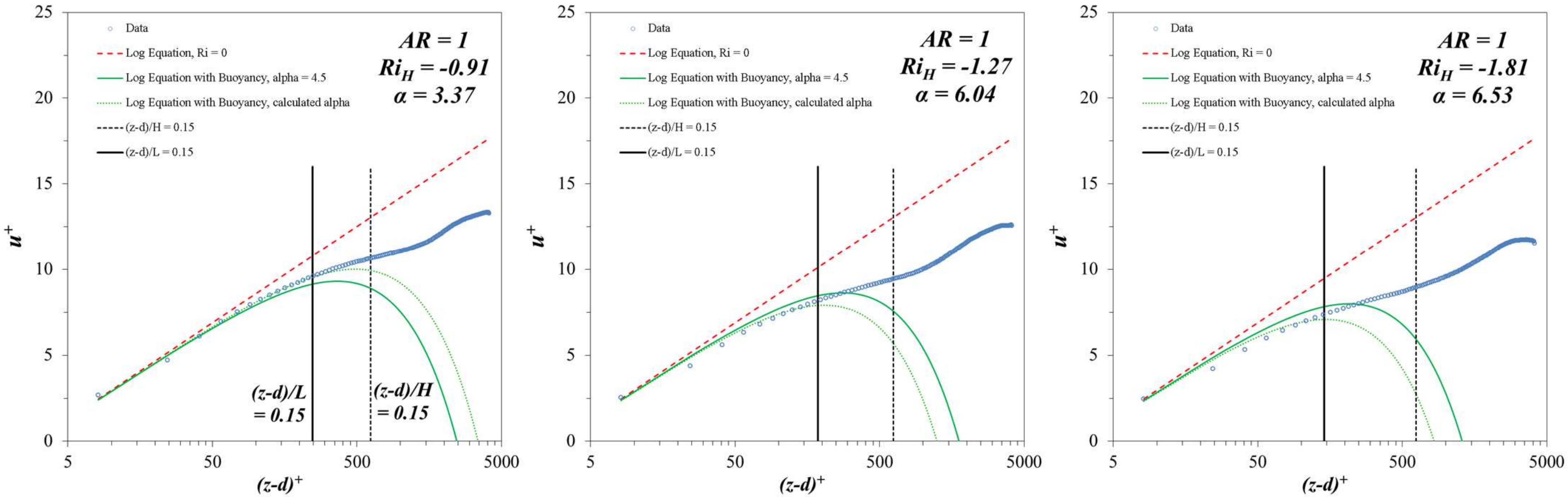






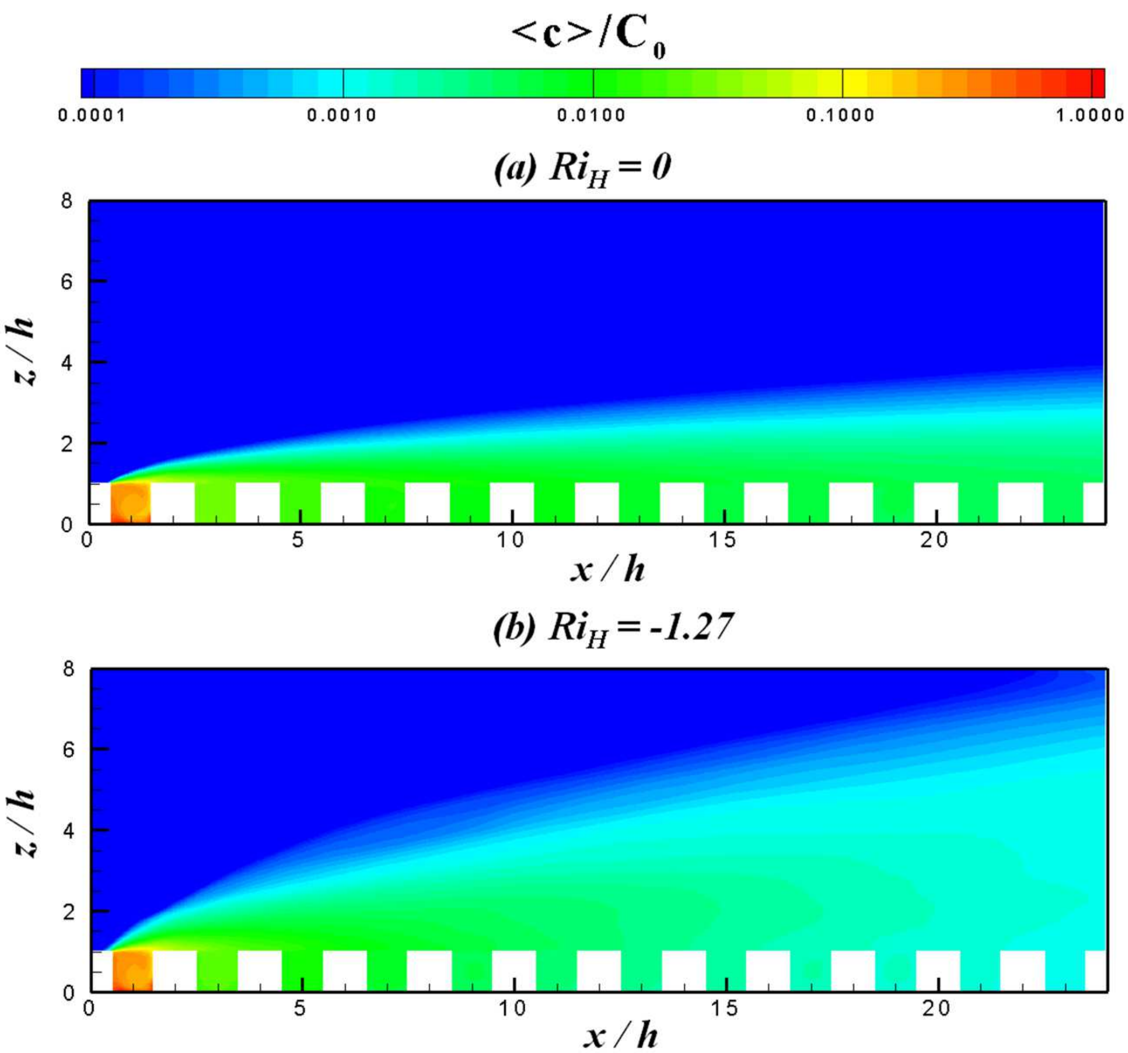
Logarithmic law of the wall

- Further increasing the intensity of instability, the wind profiles are not well described by the equation, since z/L starts to be significant
- d & z_0 also varies with instability (Ri)
- For very strong instability, buoyancy force changes the flow mechanism, thus another function of ϕ_M should be applied



Plume dispersion above urban roughness

- Constant area source on 1st street canyon ground
- Upward plume dispersion is promoted in unstable stratification
- Due to the enhanced turbulent mixing
- Less influence on the downstream areas



Conclusions

- The LES results show similar trends compared with those of the wind tunnel study by Uehara et al. (2000)
  - The deviation in magnitudes is due to the difference in roughness geometry (2D building elements in LES & 3D in wind tunnel study)

- The logarithmic law of the wall, which includes a linear term of z/L, describes well the mean wind profile only under very slightly unstable stratification

- When the unstable stratification enhances
  1) turbulence is enhanced everywhere
  2) mean wind profile gradient is higher near urban roughness due to the enhanced shear by turbulent mixing
  3) mean wind profile deviates more from (neutral) logarithmic law of the wall because of the reduced wind speed
  4) pollutant dispersion is promoted (in the vertical direction)


Thank you