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Implication of Urban Heating on Pollutant Concentration: Urban Canopy Air Quality and Breathability

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Outline

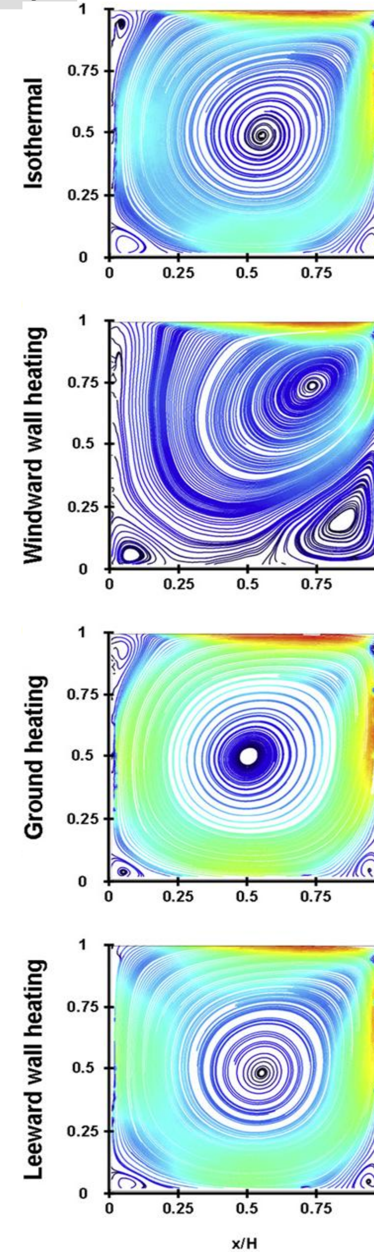
- **Introduction**
  - Background
  - Objective and Motivations
- **Methods**
  - Model Description and Numerical Settings
  - Simulation Set-up
  - Time-space averaging
- **Characterization of Unstable Flow Field**
  - Diurnal Non-uniform Heating of Urban Surfaces
  - Momentum Versus Buoyancy Forcing
  - Diurnal variation of Horizontal and Vertical Richardson Numbers
- **Results**
  - Flow and dispersion fields
  - Breathability in Urban Street Canyons
- **Summary and Conclusion**

Introduction and Background

Pollutant Concentration
- Emission
- State of the Atmosphere
  - Local Ambient Condition
  - Roughness Morphology
  - Thermal Stratification

Sini et al. 1996

“The differential heating of street surfaces largely influences the transport and pollutants exchange .”



Huang et al. 2015

Allegrini et al 2013

Objectives and Motivations

1. How to improve the CFD simulations of street-scale urban environment?

COMPREHENSIVE:

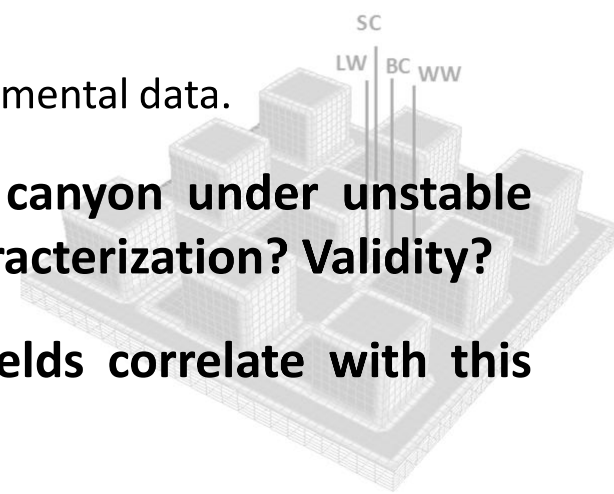
- Indoor-Outdoor building energy model, flow field, and pollutant dispersion,
- Solar load, soil layers and realistic wind and temperature profiles.

REALISTIC:

- Three-dimensional realistic and transient heating due to solar radiation and shading,
- 3-D compact mid-rise urban industrial/residential zones with low vegetation.

ADVANCED NUMERICAL MODELING:

- Large Eddy Simulation model and validation against experimental data.



2. How to comprehensively characterize the street canyon under unstable conditions? What are the factors that modify this characterization? Validity?

3. How do the flow, temperature and dispersion fields correlate with this characterization method?

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Model Description

TUF-IOBES

"Temperature of Urban Facets, Indoor-Outdoor Building Energy Simulator"

- Real weather conditions
- Building and urban material properties
- Composition of the building envelope (e.g. windows, insulation)
- waste heat from air-conditioning systems
- Indoor heat sources

PALM

"The PArallelized Large-eddy simulation Model (PALM)"

The Filtered, incompressible Boussinesq equations

-The 1st law of thermodynamics

The subgrid-scale (SGS) turbulent kinetic energy (TKE) equation

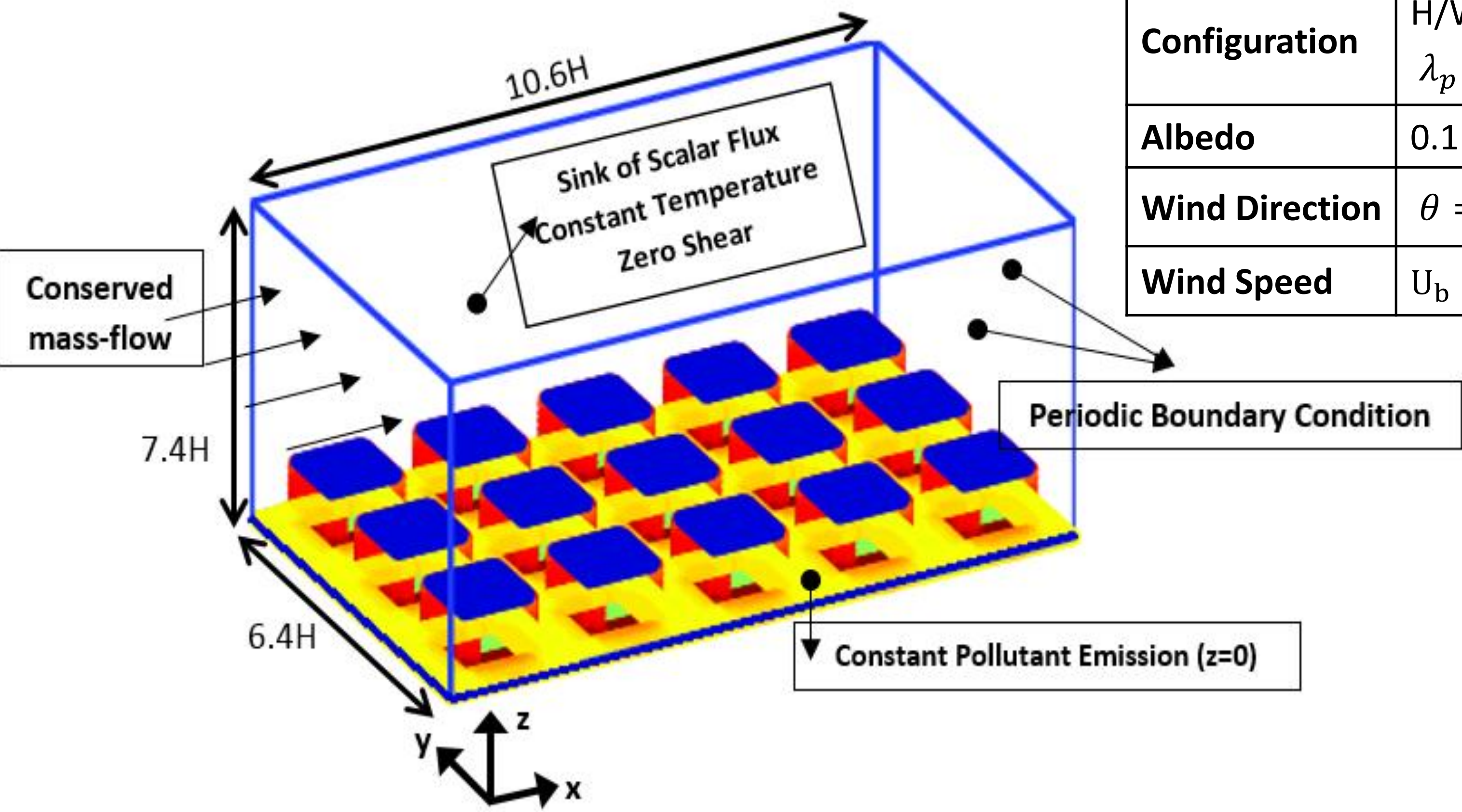
- Passive scalar (pollutant) equation

[1] Raasch, Siegfried, and Michael Schröter. "PALM–a large-eddy simulation model performing on massively parallel computers. "*Meteorologische Zeitschrift* 10.5 (2001): 363-372.
[2] Yaghoobian, Neda, and Jan Kleissl. "An Improved Three-Dimensional Simulation of the Diurnally Varying Street-Canyon Flow." *Boundary-Layer Meteorology* 153.2 (2014): 251-276.

Simulation Setup

Computational Domain	Matrix of 5x3 Cuboid buildings
Simulation Site	Boston, Massachusetts Latitude of 42° July 6-8th Average daily temperature
Configuration	H/W=1 $\lambda_p = 0.29, \lambda_f = 0.25$
Albedo	0.1 (ground) – 0.3 (walls)
Wind Direction	$\theta = 0°$ from EW
Wind Speed	$U_b = 0.5, 1, 2, 3 \text{ m s}^{-1}$

Figure 1- *Schematic of the computational domain*



LES Simulations: Time-Space Averaging Unit

Variability of results in spanwise direction

- Coceal et al 2007 – DNS simulation of flow over a matrix of cubes

  "Roll Like circulations with axes in the streamwise direction"

  " Statistics should be collected over 200-400 large eddy turn over time"

***Figure 2-** Contour plots of streamwise velocity ($\frac{u}{U_b}$)*

***30 minutes** averaged results*

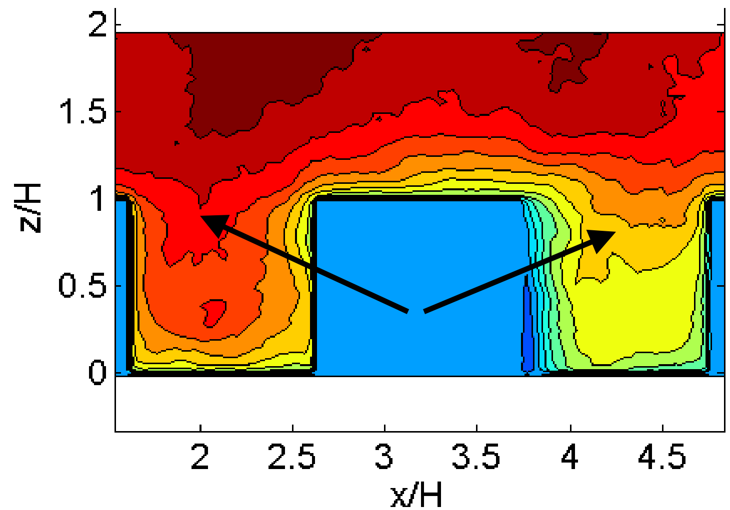
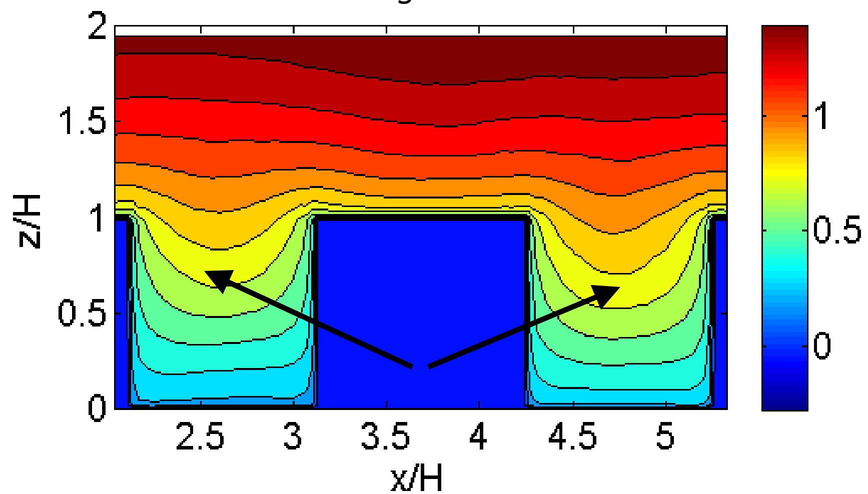


***Figure 3 -** Contour plots of streamwise velocity ($\frac{u}{U_b}$)*

*averaged over **11hrs***



[1] Coceal, O., A. Dobre, T. G. Thomas, and S. E. Belcher. "Structure of turbulent flow over regular arrays of cubical roughness. " *Journal of Fluid Mechanics* 589 (2007): 375-409.

LES Simulations: Time-Space Averaging Unit

Ensemble-averaging statistics over the repeating units to improve the effective averaging time

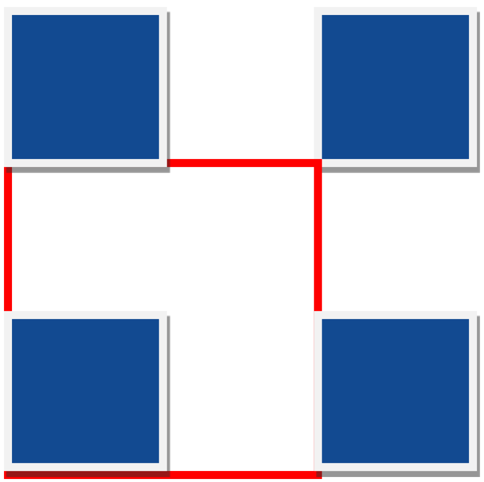
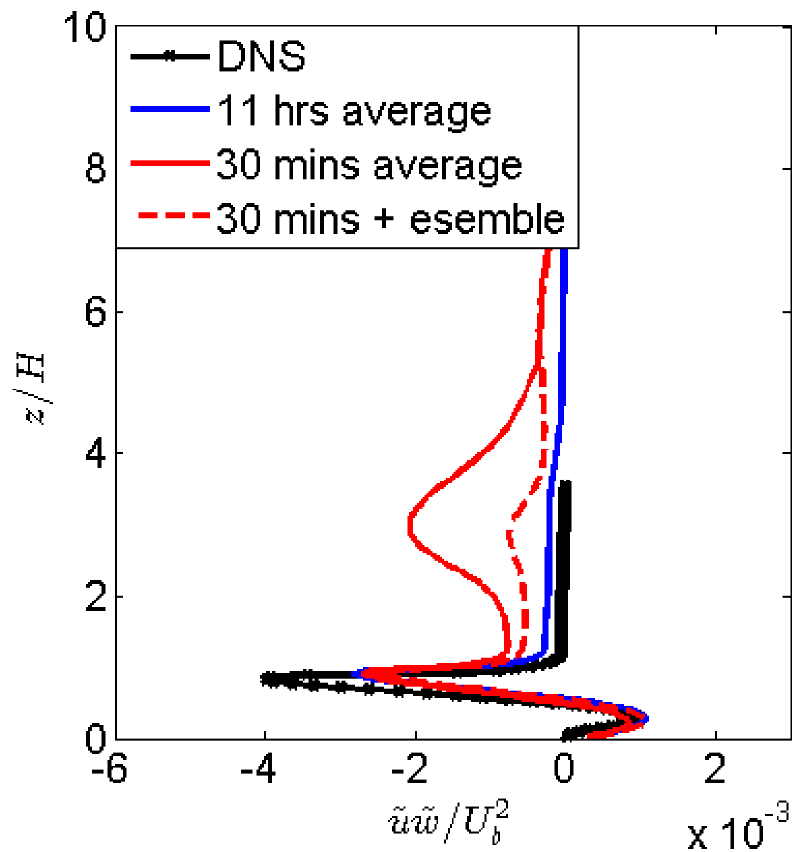


Figure 4 *- sub domain unit as shown by the red square. The total domain consist of 5*3 times the subdomain*



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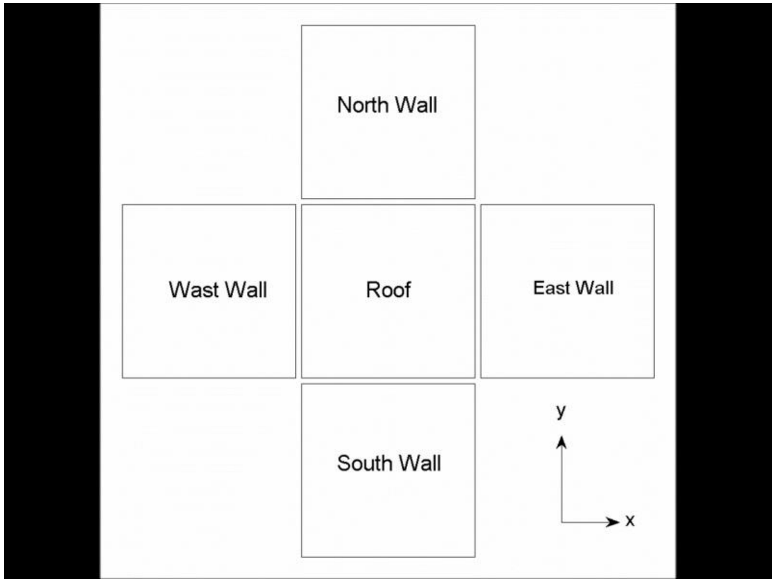
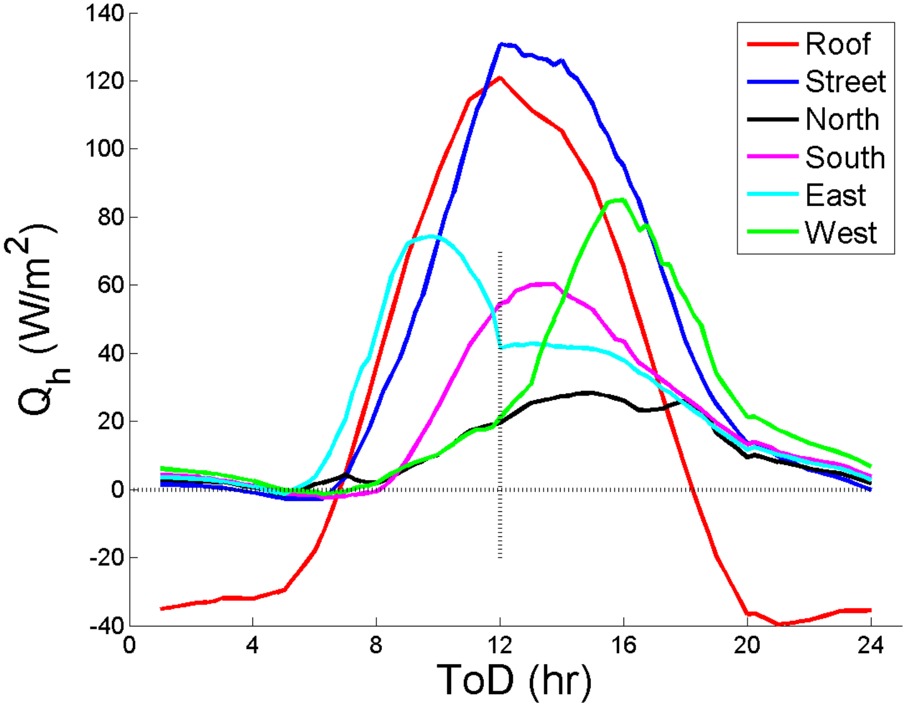
Diurnal Non-Uniform Heating of Urban Surfaces

- Clear Summer Day at Latitude of 42 degree





[1] Nazarian, N., Kleissl, J . "Realistic Solar Heating in Urban Areas: Air Exchange and Street-Canyon Ventilation", *Building and Environment, 2015, Accepted pending revision.*

Buoyancy and Momentum Forcing

- Two different Richardson numbers are defined to characterize the flow at different time of the day (ToD).
- Ri_v indicates the vertical atmospheric stability and Ri_h is the measure for wall heating orientation and strength.

Gradient Ri Number

$$Ri_v = \left(\frac{gH}{U_b^2}\right)\frac{T_H - T_g}{T_a}$$

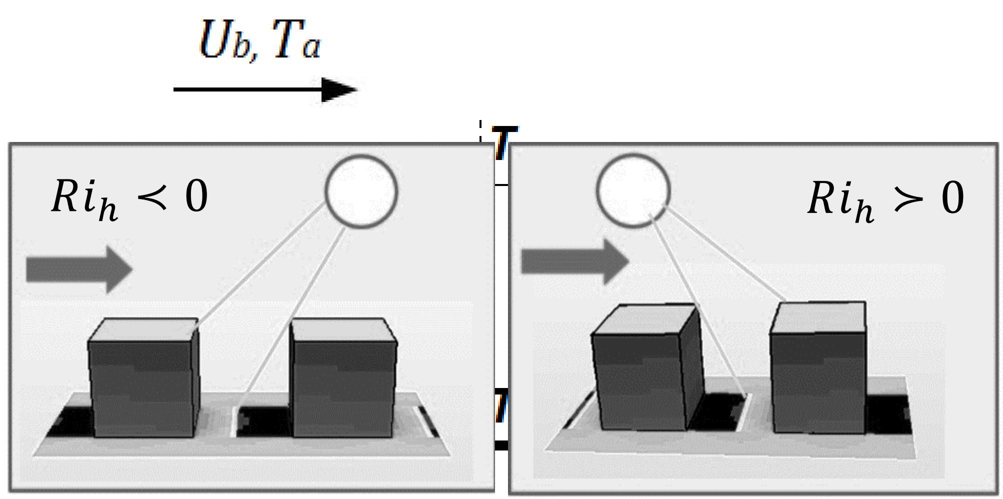
$$Ri_b = \frac{\frac{g}{\bar{T}}\frac{\partial \bar{T}}{\partial z}}{\left(\frac{\partial \bar{U}}{\partial z}\right)^2 + \left(\frac{\partial \bar{V}}{\partial z}\right)^2}$$

$$Ri_h = \frac{\frac{g}{\bar{T}}\frac{\partial \bar{T}}{\partial x}}{\left(\frac{\partial \bar{U}}{\partial z}\right)^2} \approx \frac{\frac{g}{T}\frac{T_W - T_L}{W}}{\left(\frac{U_b}{H}\right)^2} =$$

Bulk Ri Number

$$Ri_b = \frac{g\Delta\bar{T}\Delta z}{\bar{T}\left[(\Delta\bar{U})^2 + (\Delta\bar{V})^2\right]}$$

$$= \left(\frac{gH}{U_b^2}\right)\frac{T_W - T_L}{T_a}\left(\frac{H}{W}\right)$$



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Diurnal Variation of Richardson Numbers

AC – Assisting Condition - $Ri_h < 0$

HH – Horizontal Heating - $Ri_h \simeq 0$

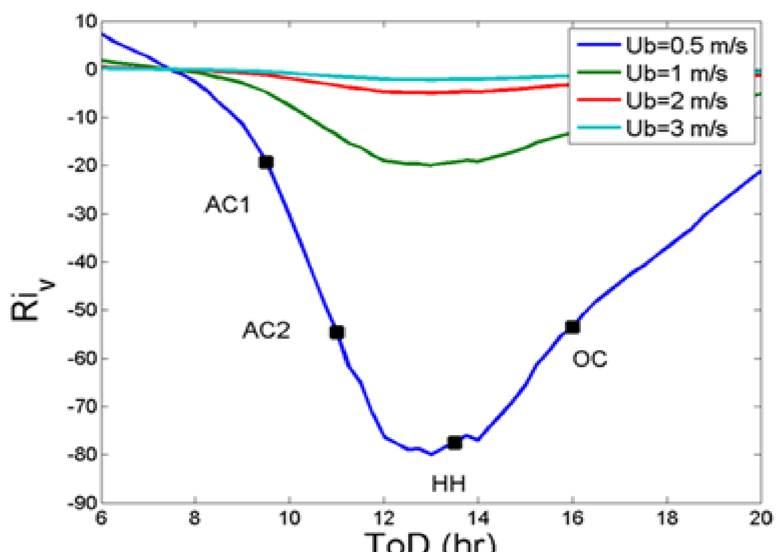
OC – Opposing Condition - $Ri_h > 0$

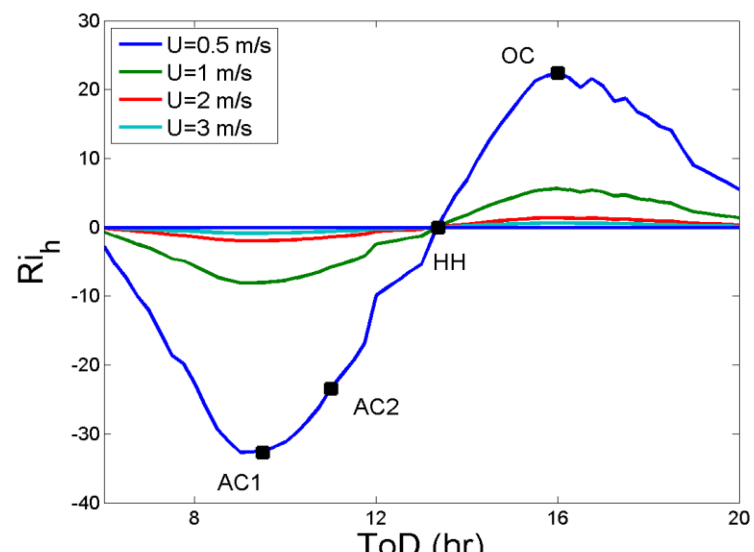
Ri_v indicates the vertical atmospheric stability and Ri_h is the measure for wall heating orientation and strength

$U_b = 0.5$ m/s	AC1	AC2	HH	OC
Time of Day (EDT)	0930	1100	1330	1600
$Ri_v(BC)$	-19.2	-54.5	-77.5	-53.6
$Ri_h(BC)$	-32.7	-23.4	0	22.5

$$Ri_v = \left(\frac{gH}{U_b^2}\right)\frac{T_H - T_g}{T_a}$$

$$Ri_h = \frac{\frac{g\partial T}{T\partial x}}{\left(\frac{\partial \bar{U}}{\partial z}\right)^2} \approx \left(\frac{gH}{U_b^2}\right)\frac{T_W - T_L}{T_a}\left(\frac{H}{W}\right)$$





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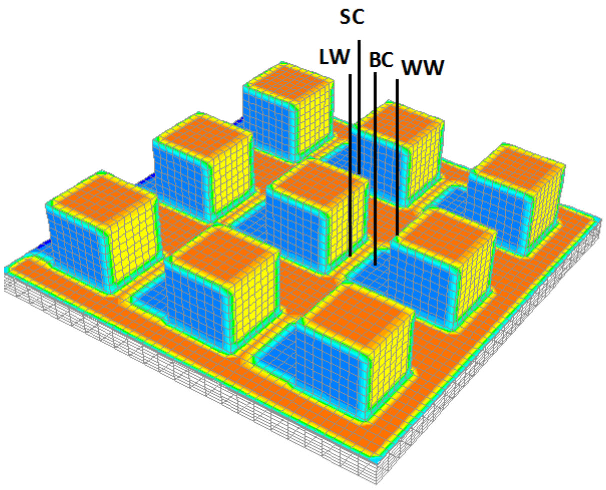
Results

- PART 1 - FLOW FIELD and DISPERSION
  - Contour plots of flow, temperature and concentration
  - Vertical Profile of turbulent fluxes at different locations
- PART 2 - Air Quality and Breathability
  - Pollutant concentration at pedestrian level
  - Air Exchange Rate and Pollutant Exchange Rate



Flow Field and Dispersion

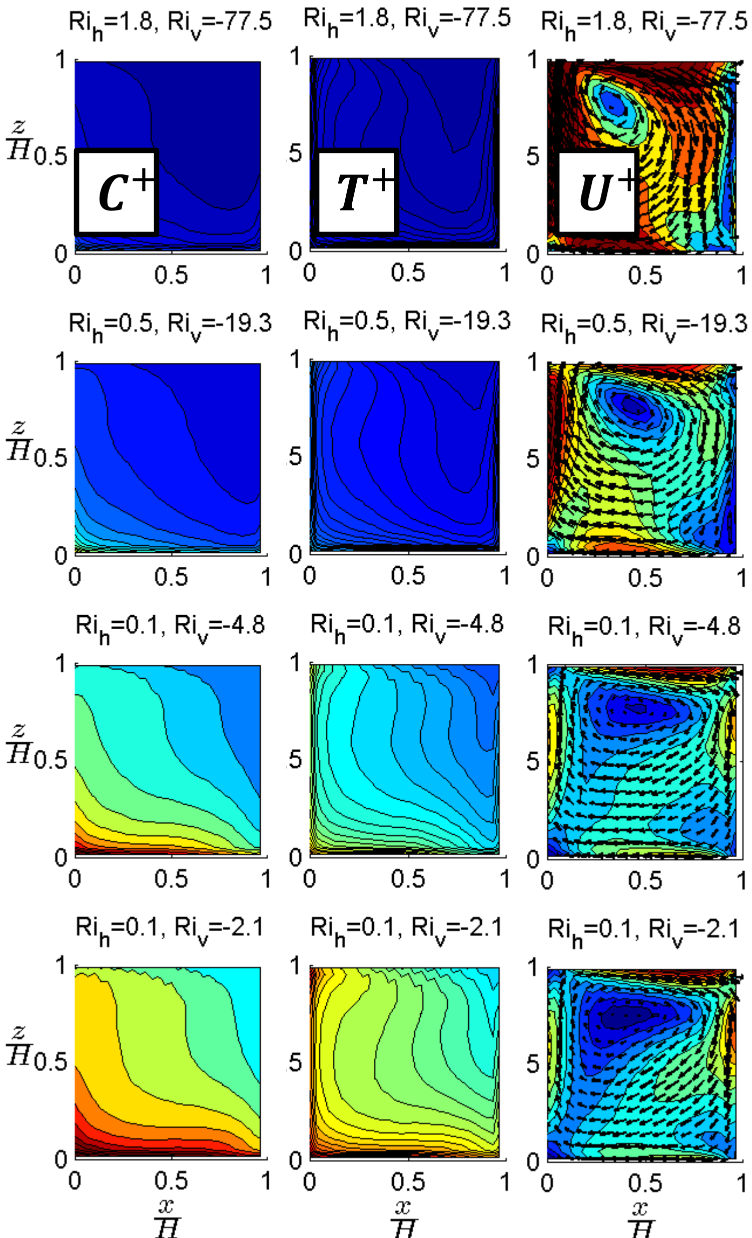
Contour plots of normalized mean velocity magnitude, temperature and concentration field

Horizontal Heating (1330EDT), $\boldsymbol{Ri_{h\simeq}0}$, **Max** $\boldsymbol{Ri_v}$

- **AR=1**
- **Vertical** plane in the center of building canyon
- **Time-Ensemble Averaged** for 1800s and 15 subdomain units
- Ub=0.5, 1, 2, 3 m/s

$$C^+ = \frac{C - C_{ref}}{E.H/U_b}$$

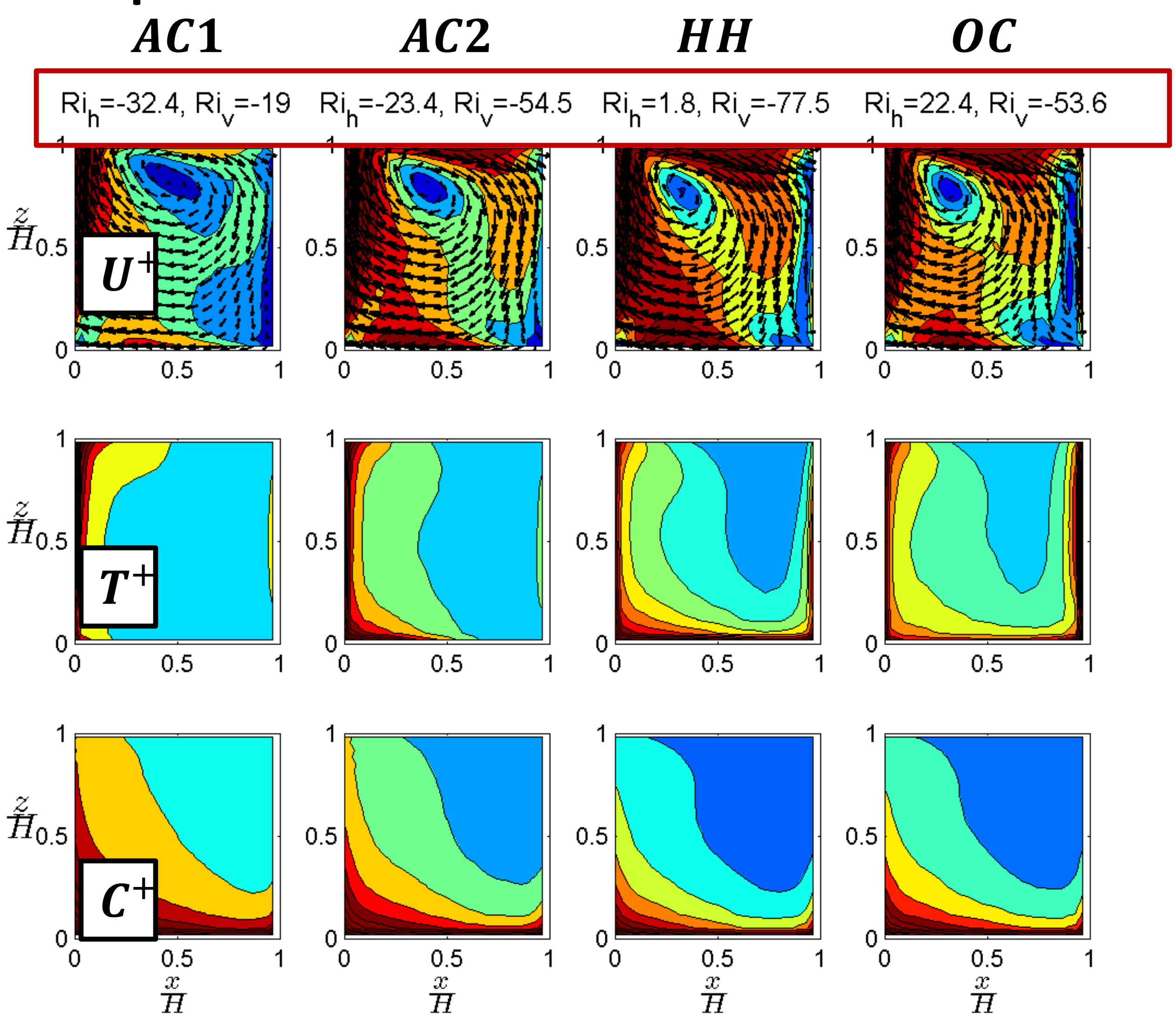
$$T^+ = \frac{T - T_{ref}}{Q_h/U_b}$$



Flow Field and Dispersion

Contour plots of normalized mean velocity magnitude, temperature and concentration field

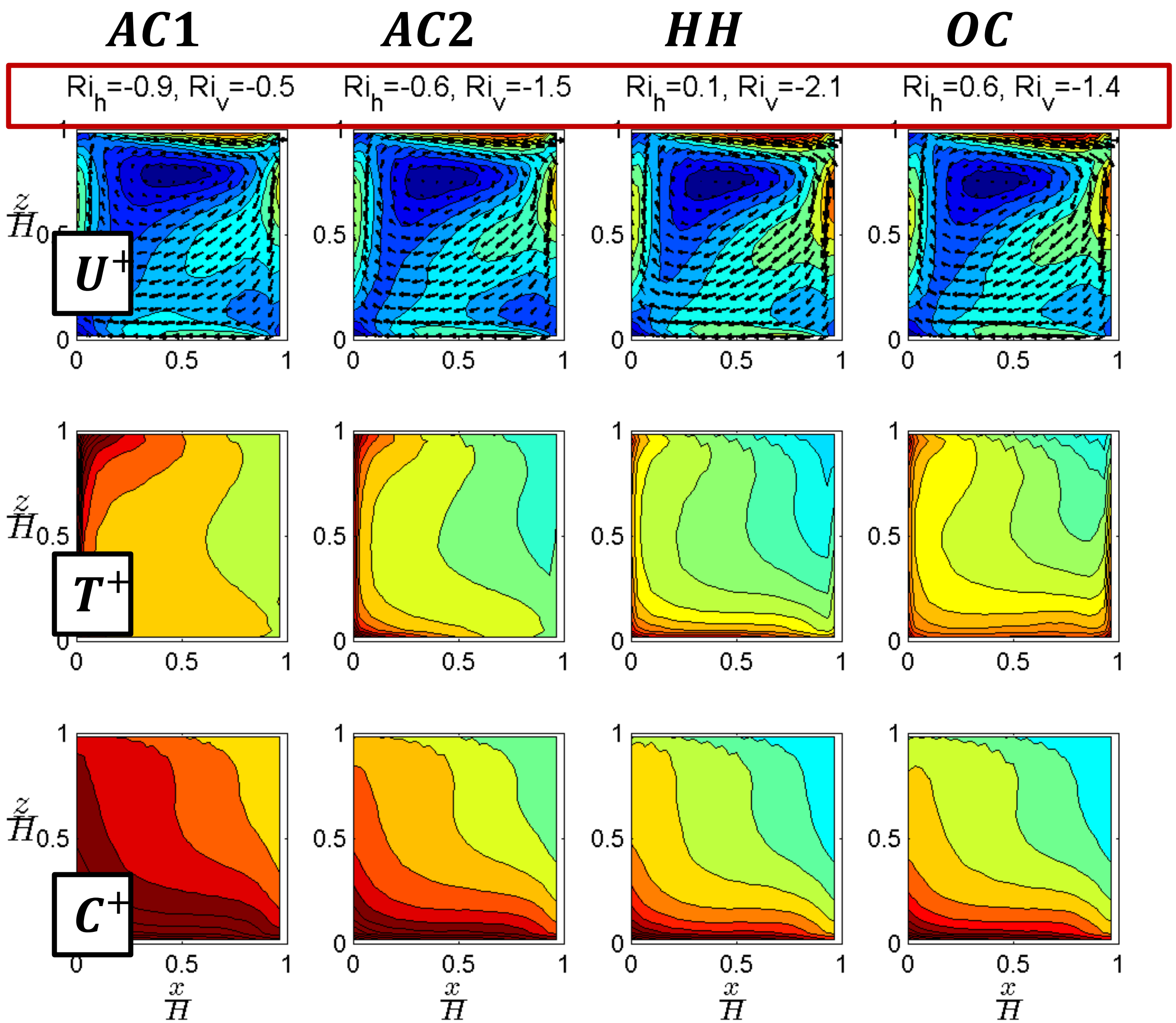
- **Diurnal Variation of Surface Heating**
- **AR=1**
- **Vertical** plane in the center of building canyon
- **Time-Ensemble Averaged** for 1800s and 15 subdomain units
- Ub=0.5 m/s



Flow Field and Dispersion

Contour plots of normalized mean velocity magnitude, temperature and concentration field

- **Diurnal Variation of Surface Heating**
- **AR=1**
- **Vertical** plane in the center of building canyon
- **Time-Ensemble Averaged** for 1800s and 15 subdomain units
- Ub=3m/s



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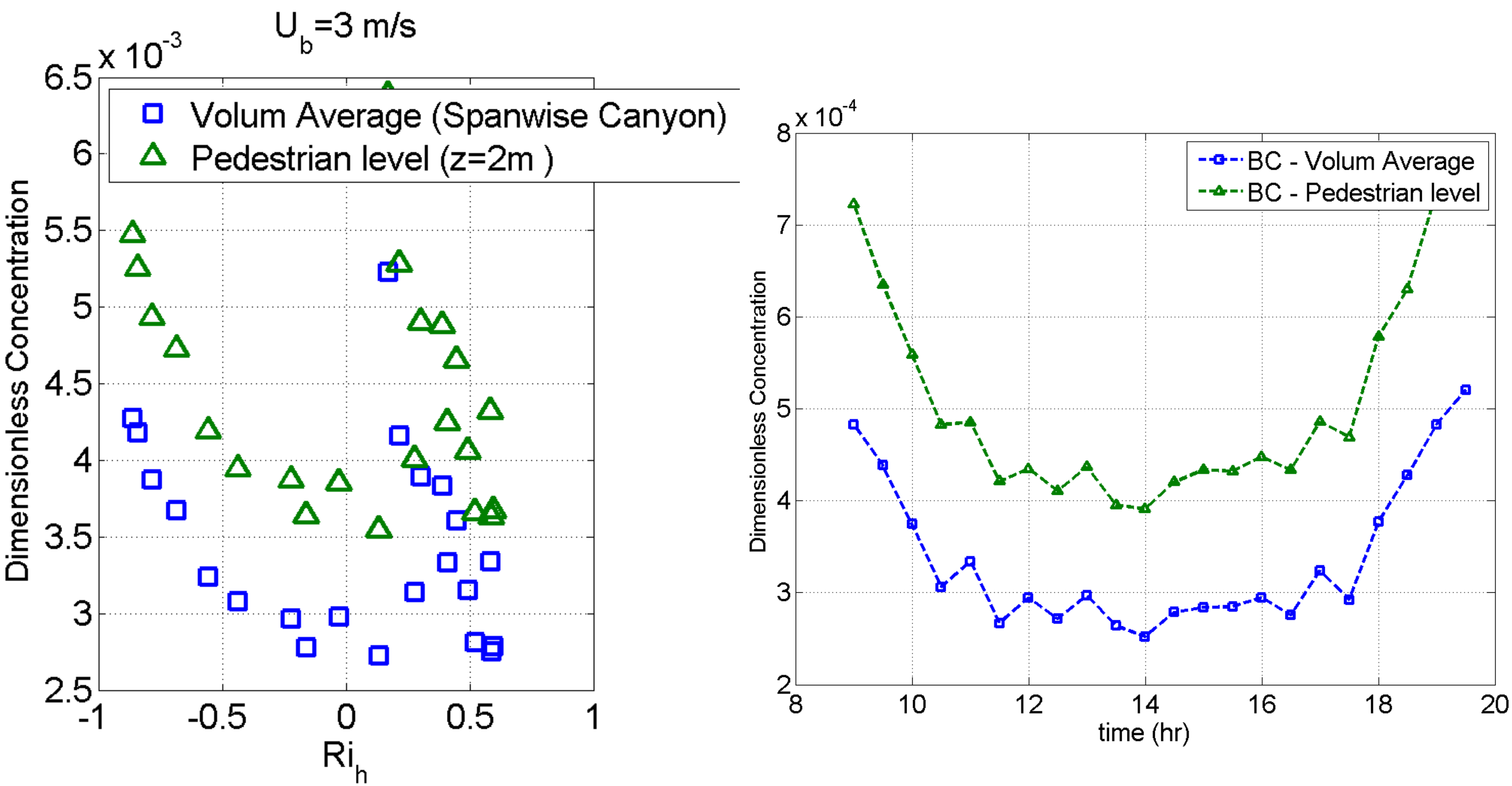
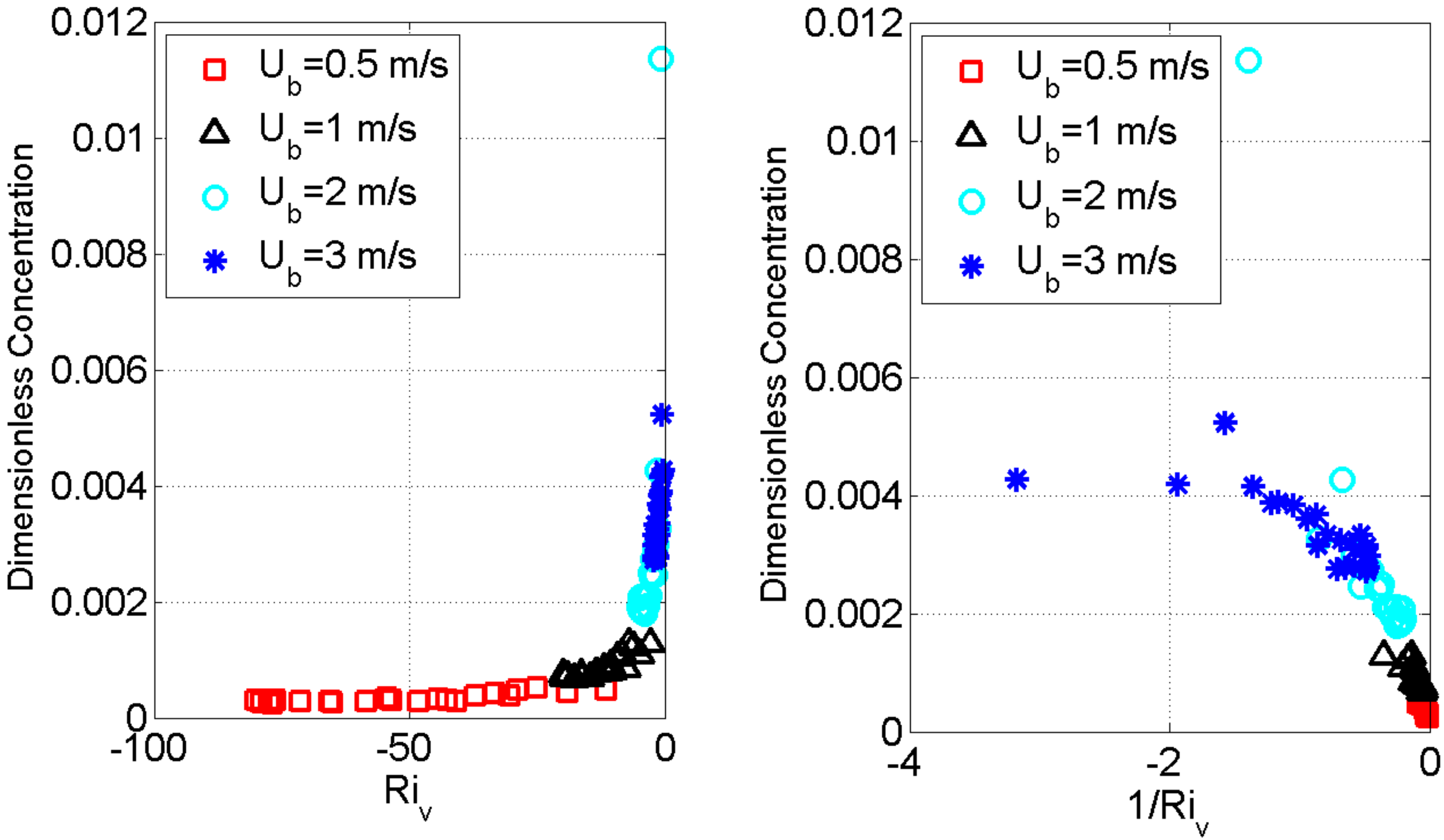
Breathability in Urban Street Canyons



Breathability in Urban Street Canyons



Conclusion and Summary

- **Project Goal:**
  - A realistic and comprehensive study of urban microclimate with LES modeling
  - Time and spatial averaging is combined for more accurate representation of flow statistics
- **Comprehensive characterization Method:**
  - Break down of the total thermal forcing in urban environments into directional forcings indicated by Ri_h and Ri_v, that are modified by surface material and radiative properties as well as wind speed and direction
  - Validity of characterization method evaluated by a similarity analysis
- **Breathability in the Urban Canyon Under Unstable Stratification**

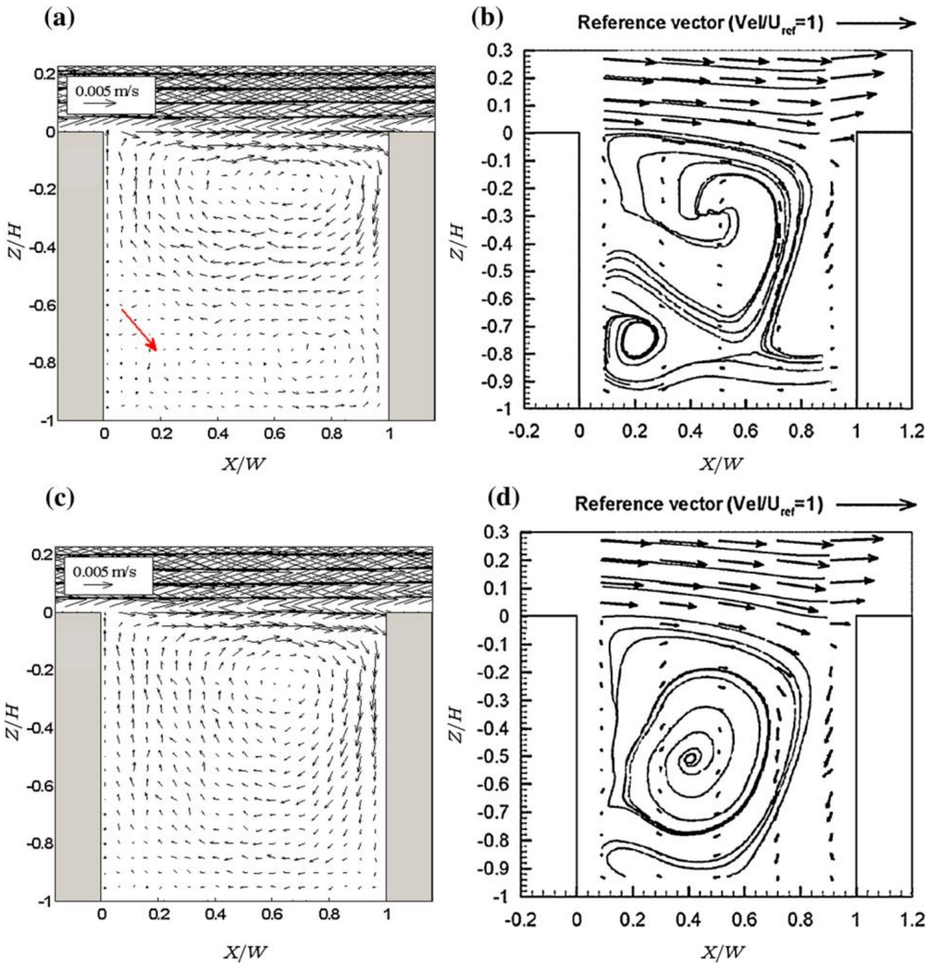
  Modification of flow field by the horizontal heating is more apparent for a strongly unstable condition

  Thermal field is strongly correlated with the sign of $\boldsymbol{Ri_h}$

  Dispersion field changes linearly as a function of $\boldsymbol{1/Ri_v}$, except for cases of high $\boldsymbol{Ri_h}$ to $\boldsymbol{Ri_v}$ ratio

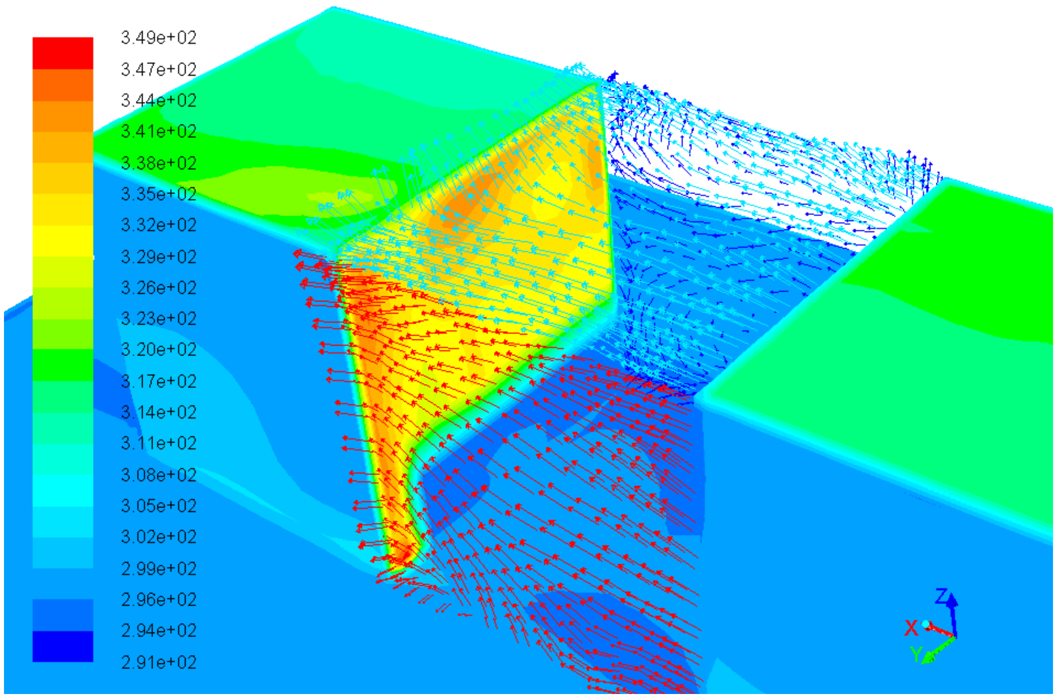
Validation of numerical models

- Velocity and temperature field of PALM validated by Park et al [1]
- TUF-IOBES validated by Yaghoobian and Kleissl [2] and the coupling method validated [3] against the wind-tunnel experiment of Kovar-Panskus et al. [4]
- The prognostic equation for passive scalars in PALM validated by Park et al. [5]



3-Dimensional Air Exchange Rate (ACH)

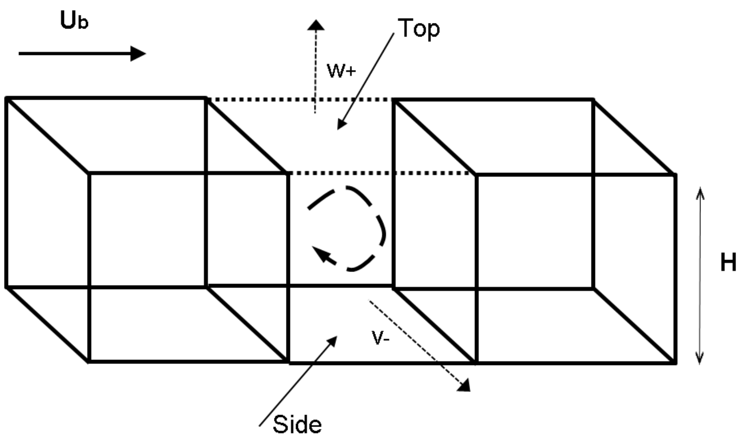
The effect of non-uniform heating on the air removal performance of street canyon



$$ACH = ACH_{top} + ACH_{side}$$

$$ACH_{top} = \frac{\iint \langle w_+ \rangle dxdy}{A_{top}}$$

$$ACH_{side} = \frac{\iint \langle v_\pm \rangle dzdy}{A_{side}}$$



3-Dimensional Air Exchange Rate (ACH)

- The effect of non-uniform heating on the air removal performance of street canyon