LES of Momentum and Heat Transport in Urban Canopies: Challenges and Applications

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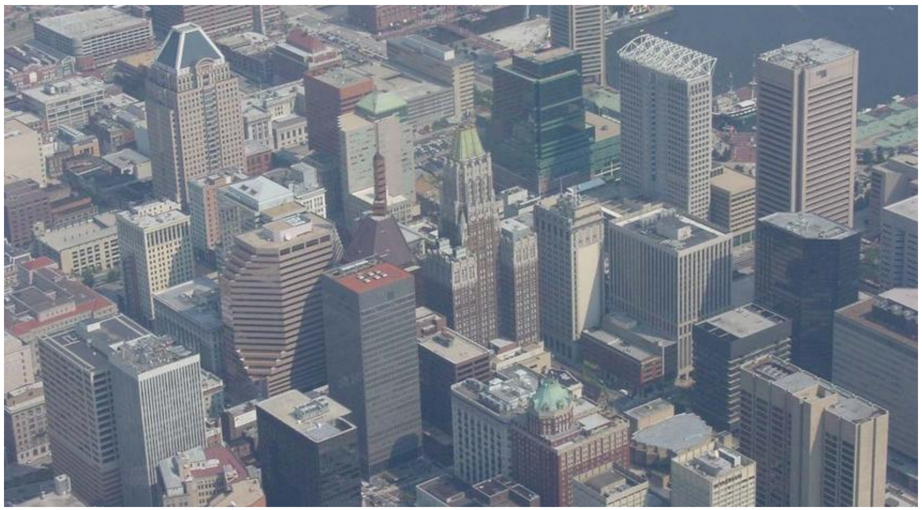
Introduction

Turbulence Scale $\xrightarrow{\text{Parameterization}}$ Regional Scale

- Better prediction of flow, temperature and mass transport within canyon
- Turbulent transport is highly sensitive to roughness length
- Need to understand both momentum and scalars in urban environments

Introduction

Real-world Problem



Laboratory-scale experiments

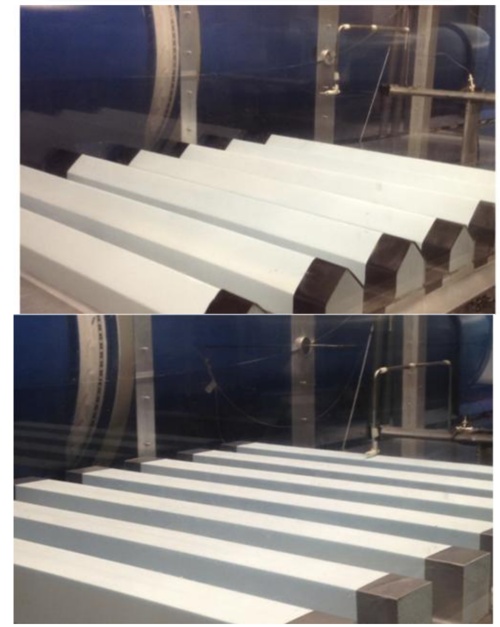


Image Courtesy: M.Munitxa, Princeton MAE wind tunnel

Pros:

✧ Details of surface heat/mass transfer

✧ Setup can be varied easily to explore effects of changing wind direction

Cons:

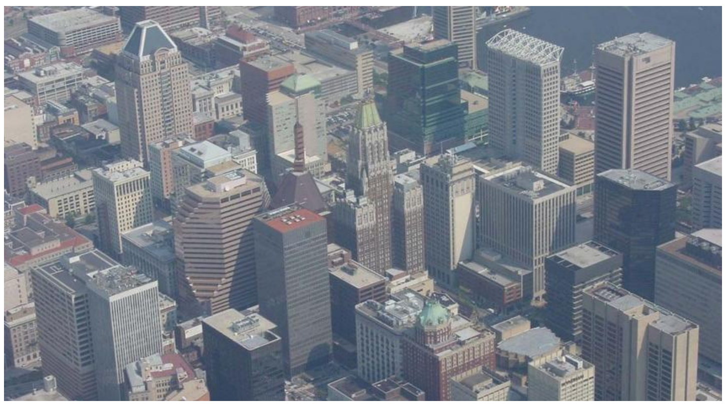
✧ Limited range of Reynolds number *(several orders lower than the real world)*

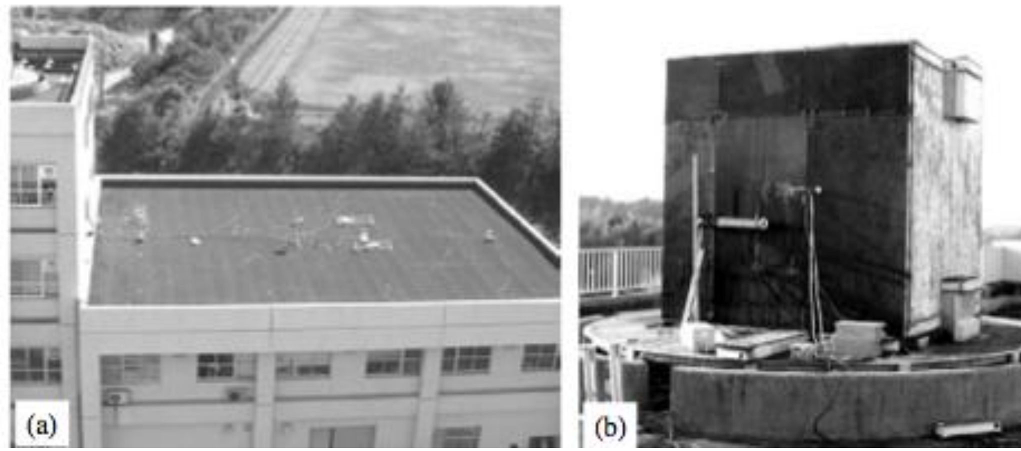
✧ Care should be taken to extend these studies to real-world problem

Introduction

Real-world Problem

Building-scale measurements





(Hagishima et al. 2003)

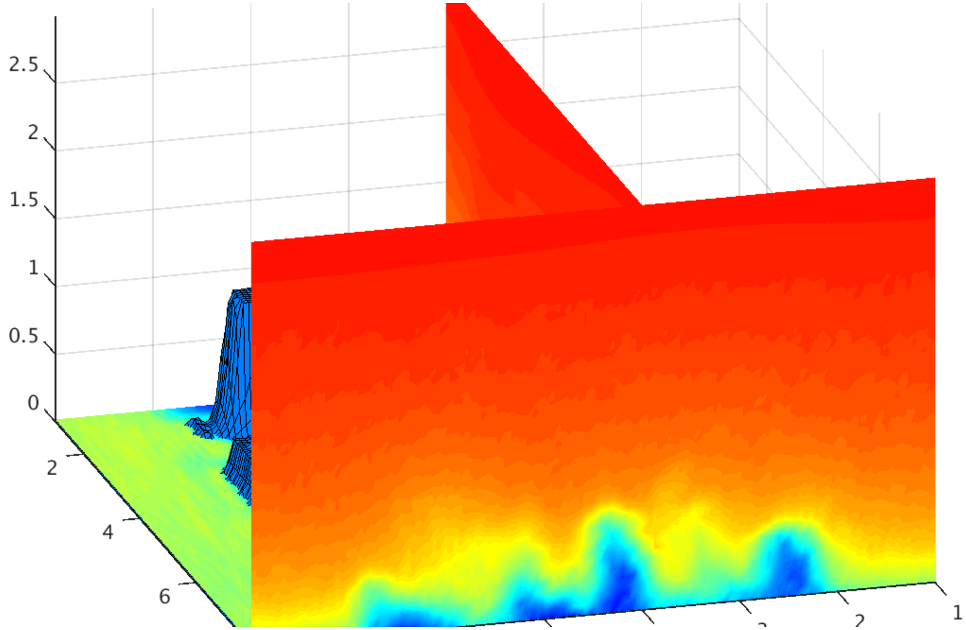
Pros:

✧ Ambient conditions are close to the real-world problem of interest

Cons:

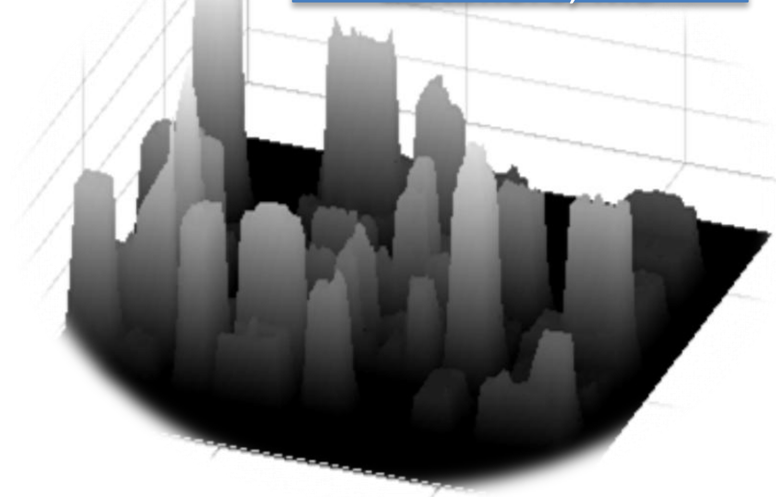
✧ Difficult to generalize because of the fine details *eg. surroundings, building shapes, etc.*

✧ Challenges in upscaling to a whole facet, whole building, and whole city due to point-wise measurement

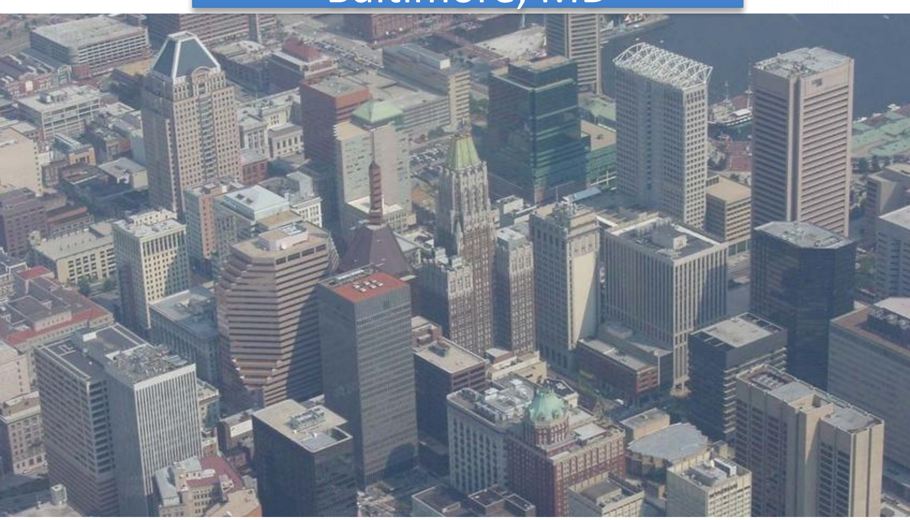


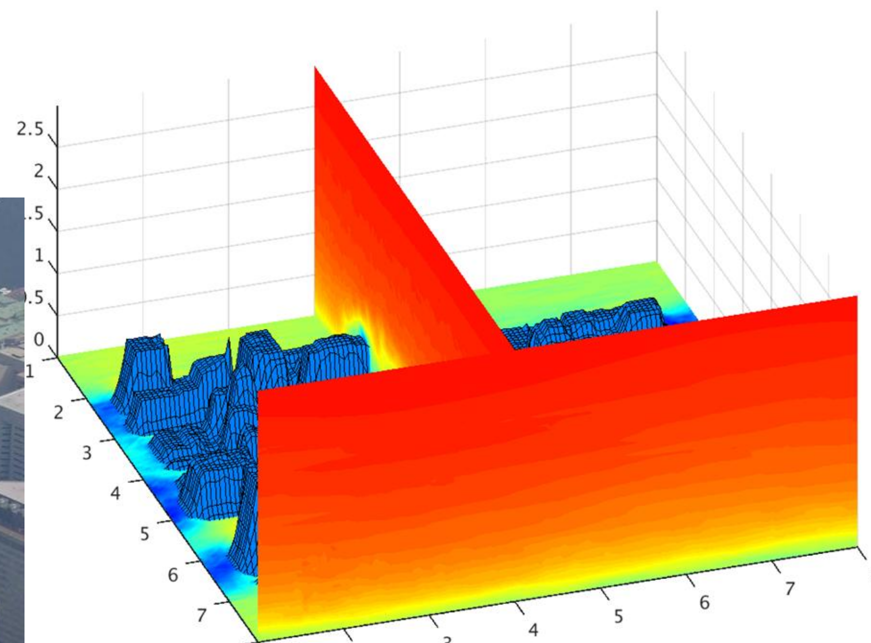
y-z slice of mean u

DEM of downtown Baltimore, MD



Aerial view of downtown Baltimore, MD





x-z slice of mean u

Motivation

- Wall-modeled LES can be a useful tool:
  - ✧ Large Reynolds number that is ~ Re_{ABL}
  - ✧ Computationally feasible
  - ✧ Apply to urban canopy to study bulk transfer properties

- Some caveats
  - ✧ Currently no wall-model for vertical surfaces when the effect of buoyancy is considered
  - ✧ Still uncertainties concerning scalar transfer when the wall-modeled approach is taken

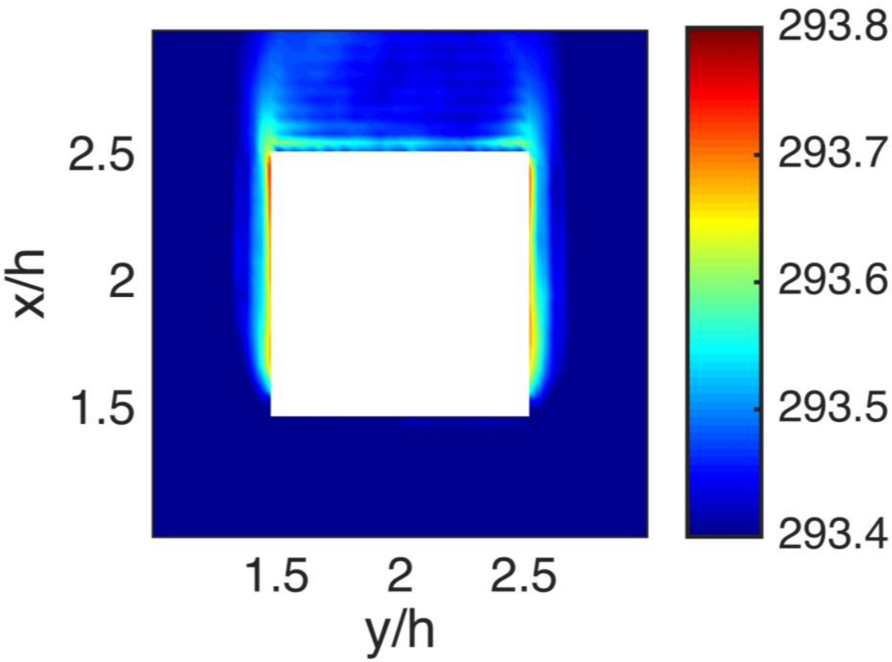
Objectives

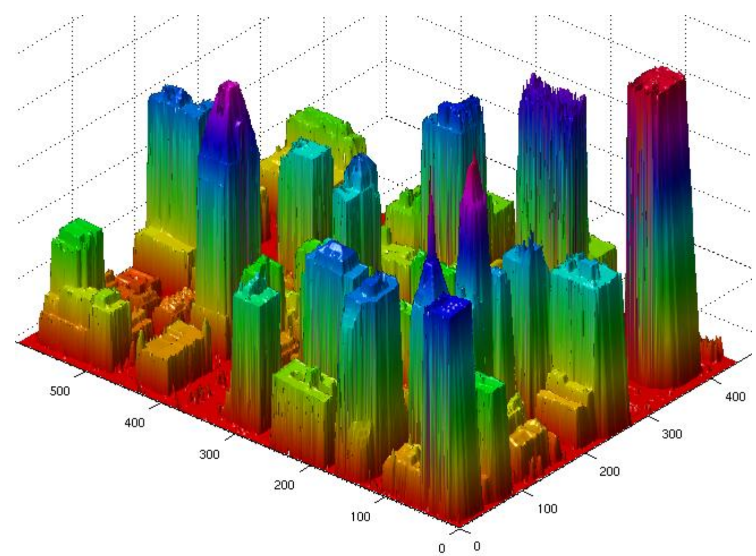
1. Assessment of wall-modeled LES and identification of some challenges

1. To apply it to study the real-world problem of interest

LES: Immersed Boundary Method

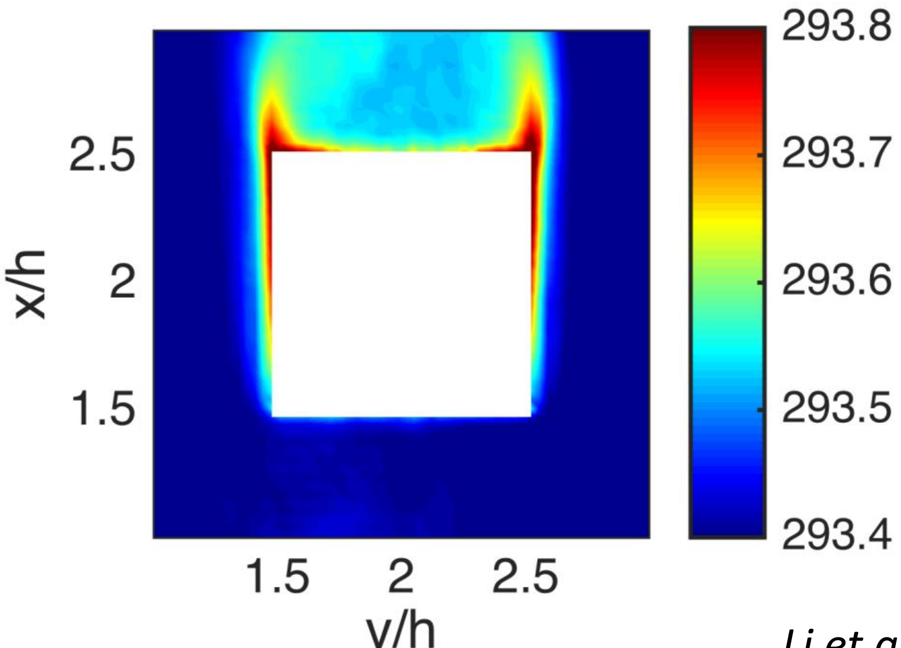
- LES with immersed boundary method => handle complex urban geometry without using body-conformal grids
- Pseudo-spectral method for speed and accuracy
- Lagrangian dynamic scale-dependent SGS

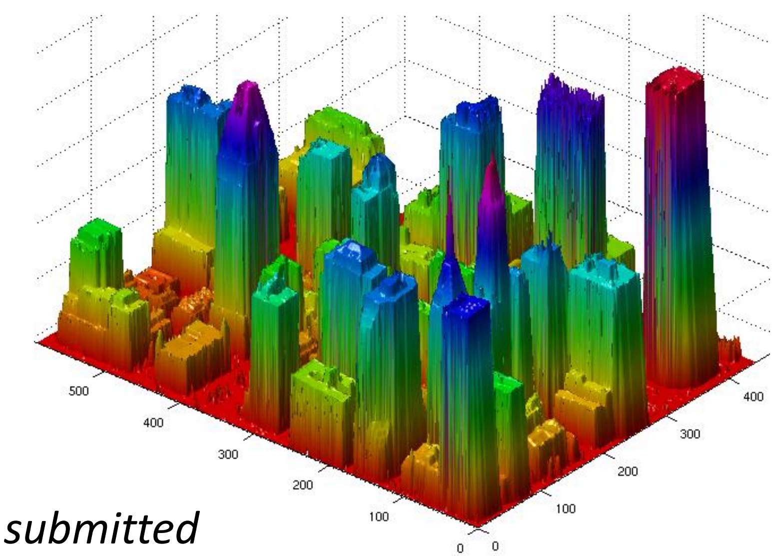




LES: Reduction of Gibbs Phenomenon

- LES with immersed boundary method => handle complex urban geometry without using body-conformal grids
- Pseudo-spectral method for speed and accuracy
- Lagrangian dynamic scale-dependent SGS





Li et al. JCP, submitted

Wall model

- ✧ A wall-model based on Kader & Yaglom (1972) for scalar transfer in turbulent flow
- ✧ Update the smooth-wall roughness lengths dynamically

Wall model for momentum

$$\left(\frac{u}{u_*}\right) = A\log\left(\frac{z}{n/u_*}\right) + B$$

Wall model for scalar

$$\frac{s_0 - s(z)}{s_*} = a\log\left(\frac{z}{n/u_*}\right) + b$$

Momentum roughness length

$$z_{0m} = \frac{n}{u_* e^{B/A}}$$

Scalar roughness length

$$z_{0s} = \frac{n}{u_* e^{b/a}}$$

u_* friction velocity

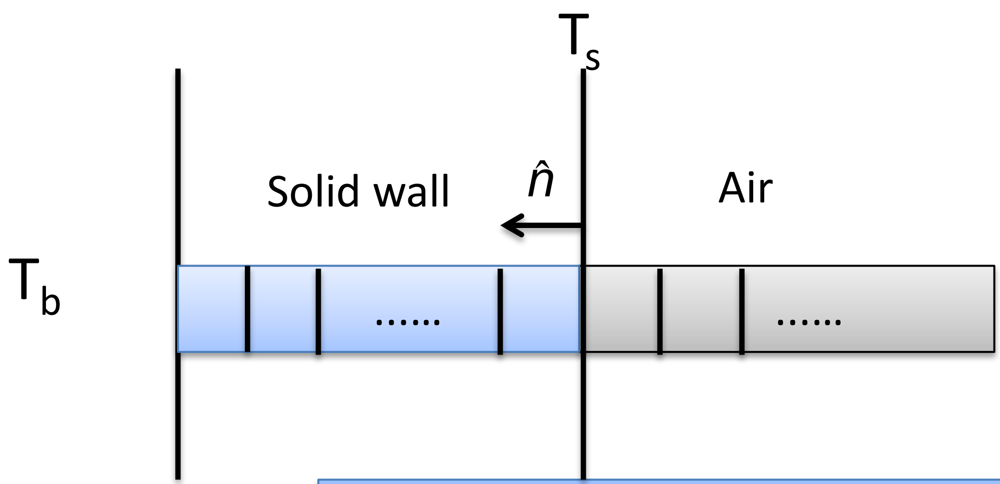
s_* scalar flux concentration

A, B, α, β empirical constants

A	B	α	β
2.43	5.1	2.00	4.0

Boundary Condition

- What is the appropriate boundary condition?



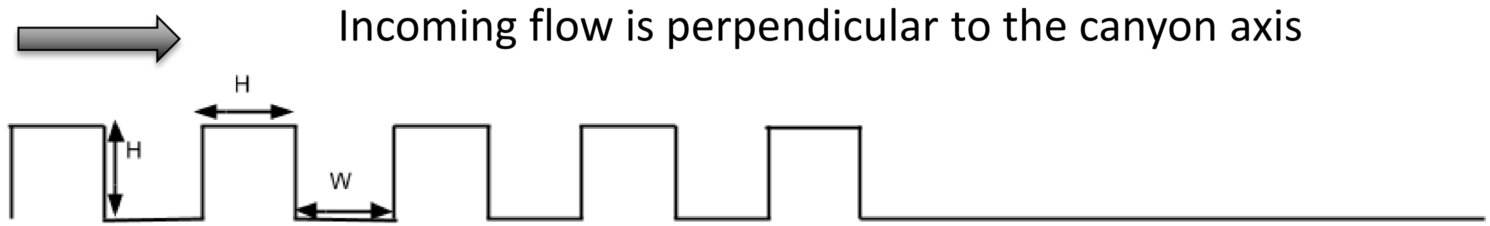
Real-world problem: urban buildings energy budget constrained BC is more realistic

Rn constrained BC: $$R_n = G + H = -\lambda \frac{\partial T}{\partial \hat{n}} + \langle w'T' \rangle \rho_{air} c_p$$

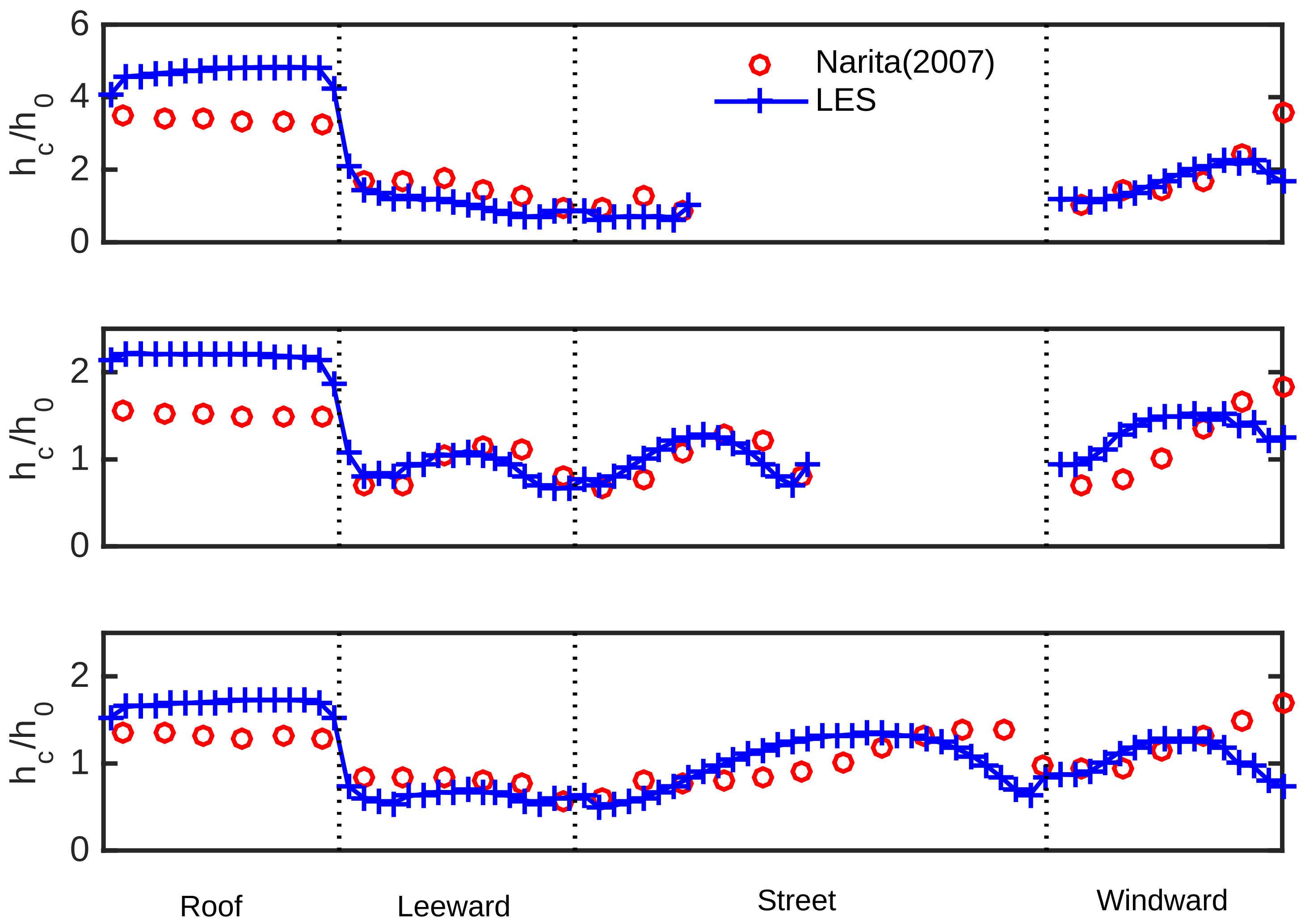
Equilibrium BC: $$G = H$$
$$-\lambda \frac{\partial T}{\partial \hat{n}} = \langle w'T' \rangle \rho_{air} c_p$$

Spatial variation of mass transfer coefficient, laboratory scale

- *Narita (2007):* measure water evaporation rate on surfaces of 2D ribs



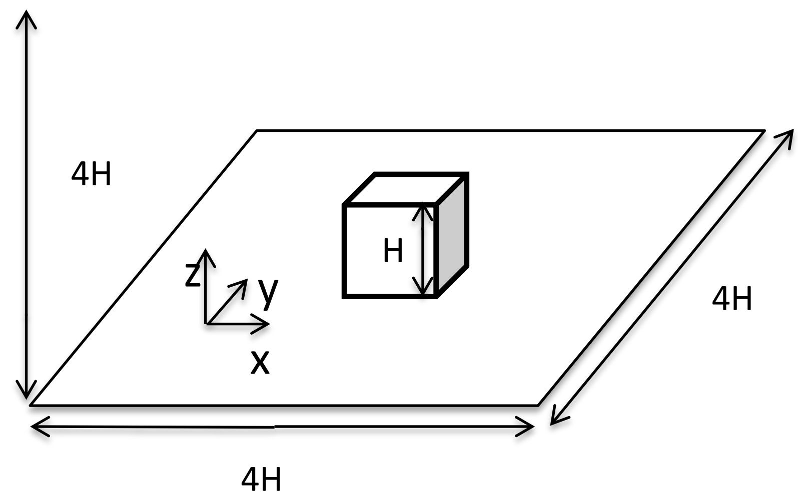
  - Horizontally periodic boundary condition
  - Domain height is 5H
  - Vary the H/W ratio according to the experiment
  - Compare mass transfer coefficient normalized



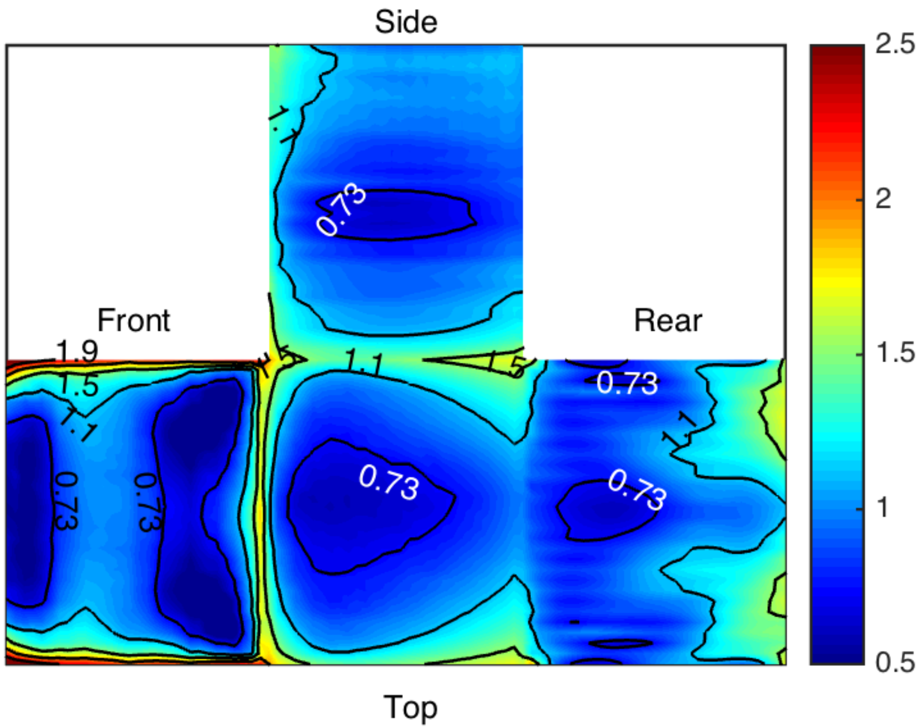
- ✧ Spatial variation of the mass transfer coefficient is captured
- ✧ % bias is about 20% averaged over all facets
- ✧ Roof surface: largest deviation
  - highly dependent on inflow conditions

Bulk relation between *Re* and *Nu*

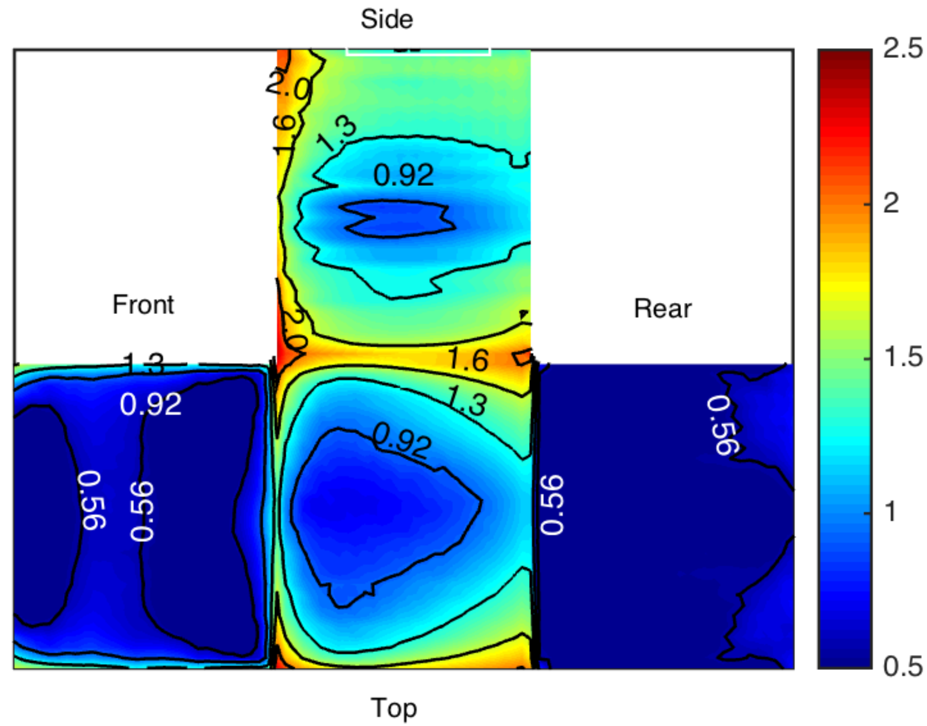
✧ *Nakamura et al. (2001):* internally heated copper cube placed in low-speed wind tunnel



- Vary *Re* by changing the horizontal pressure forcing
- Compare with empirical relation between *Nu* & *Re* obtained in the experiment



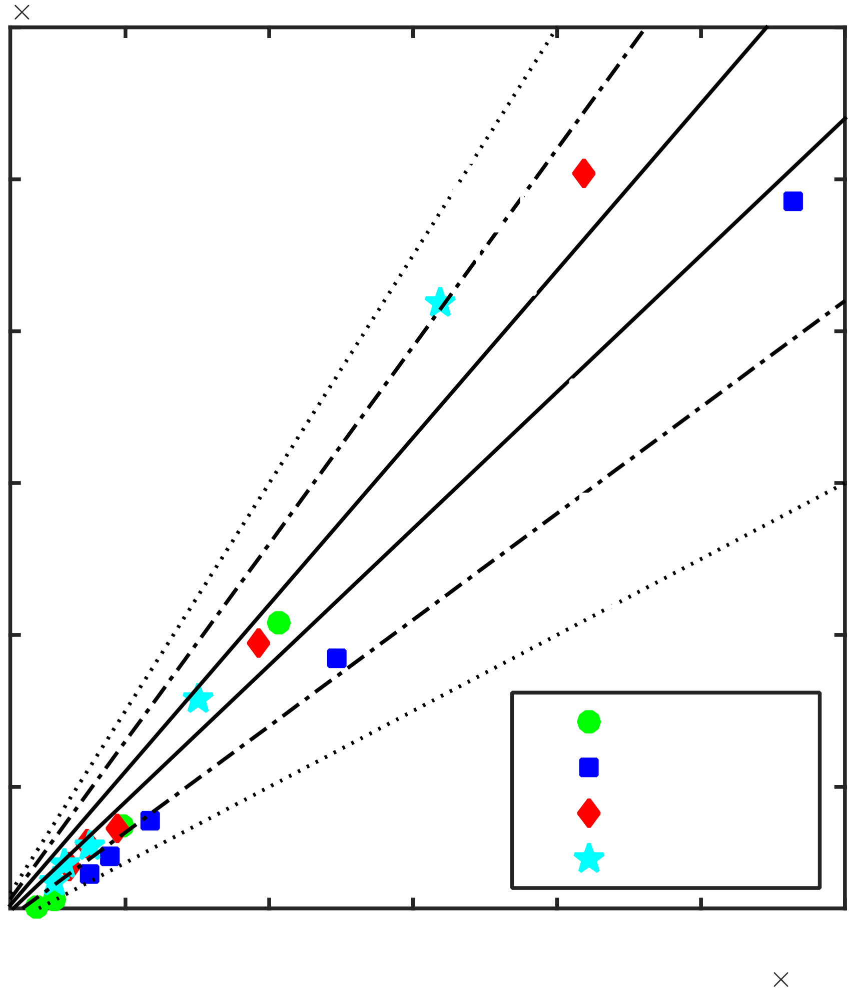
h_c **normalized by cube average** h_c



h_c **normalized by each facet average** h_c

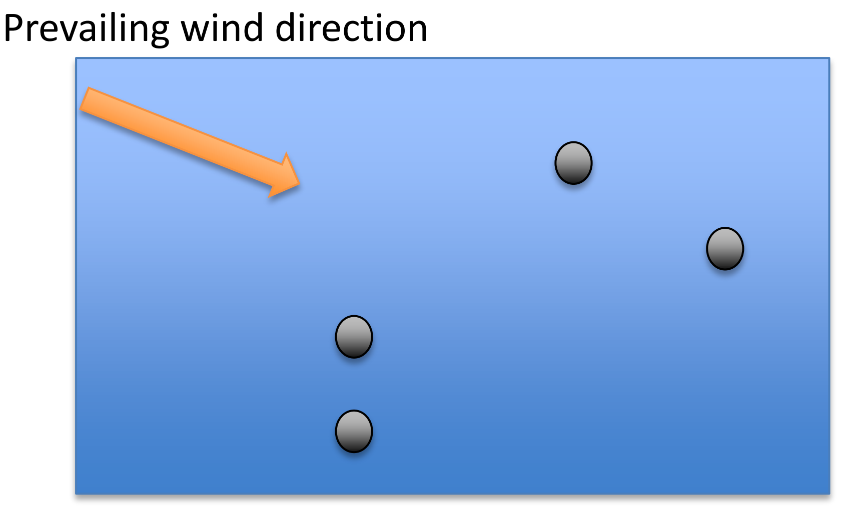
- ✧ Extreme values of h_c : at edges
- ✧ Most parts of facets only deviate "moderately" from surface mean values
- ✧ Implies: for practical applications, surface average values and cube average give reasonable estimates, especially if total heat flux is concerned.
- ✧ But point-wise field measurements could deviate by 50%

Bulk relation between *Re* and *Nu*



- ✧ Agreement with experiment: within 50%
- ✧ Reasonably good match between predicted values: $Nu=aRe^m$
- ✧ Confidence in the performance of wall-modeled LES
- ✧ Difference could be attributed to Re => presents further challenge to simply apply laboratory results to real world problem.

Bulk relation between *Re* and *Nu* in **outdoor** measurements



Experimental setup

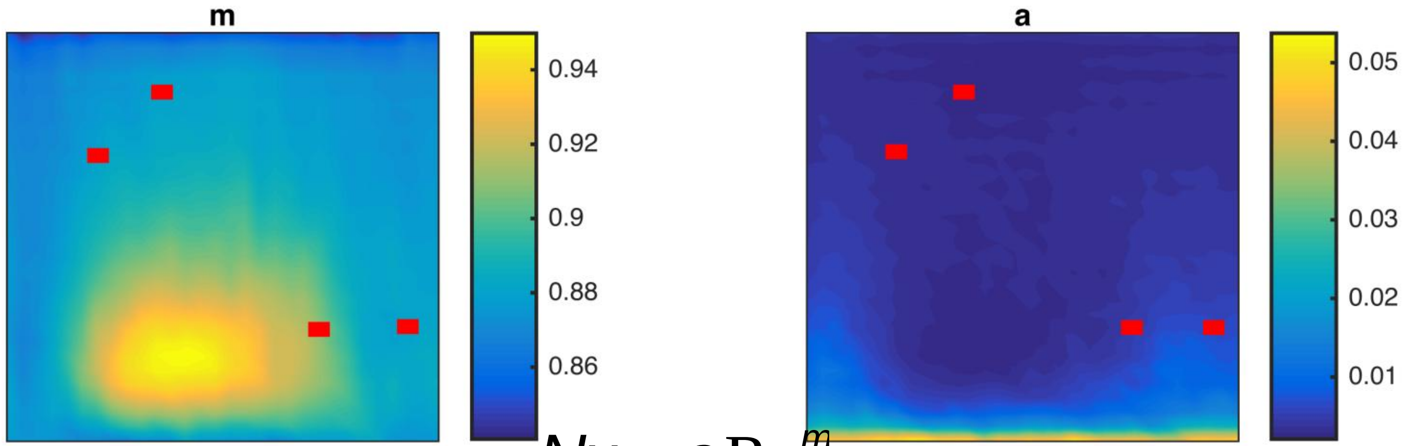
(*Hagishima et al., 2003*)

Simultaneous measurement of surface heat flux, temperature and wind velocity

Roof measurement: considered for comparison to LES

- Regression based on LES results

Bulk relation between *Re* and *Nu* in **outdoor** measurements



$$Nu = a\mathrm{Re}^m$$

	Experimental	LES
Emmel et al.[20]	0.85 (Roof)	0.87
Clear et al.[22]	0.8 (Roof)	0.87
Yazdamian and Klems[21]	0.89 (Windward, low-rise building)	0.89
	0.671 (Leeward, low-rise building)	0.90

- *m - relative* relation between wind and forced convective heat transfer
- Quantitative prediction of the relative relation from LES: comparable to outdoor experiments (mainly related to the wall-model according to Kader & Yaglom 1972)
- Absolute magnitudes of heat transfer coefficient: highly sensitive to fine details

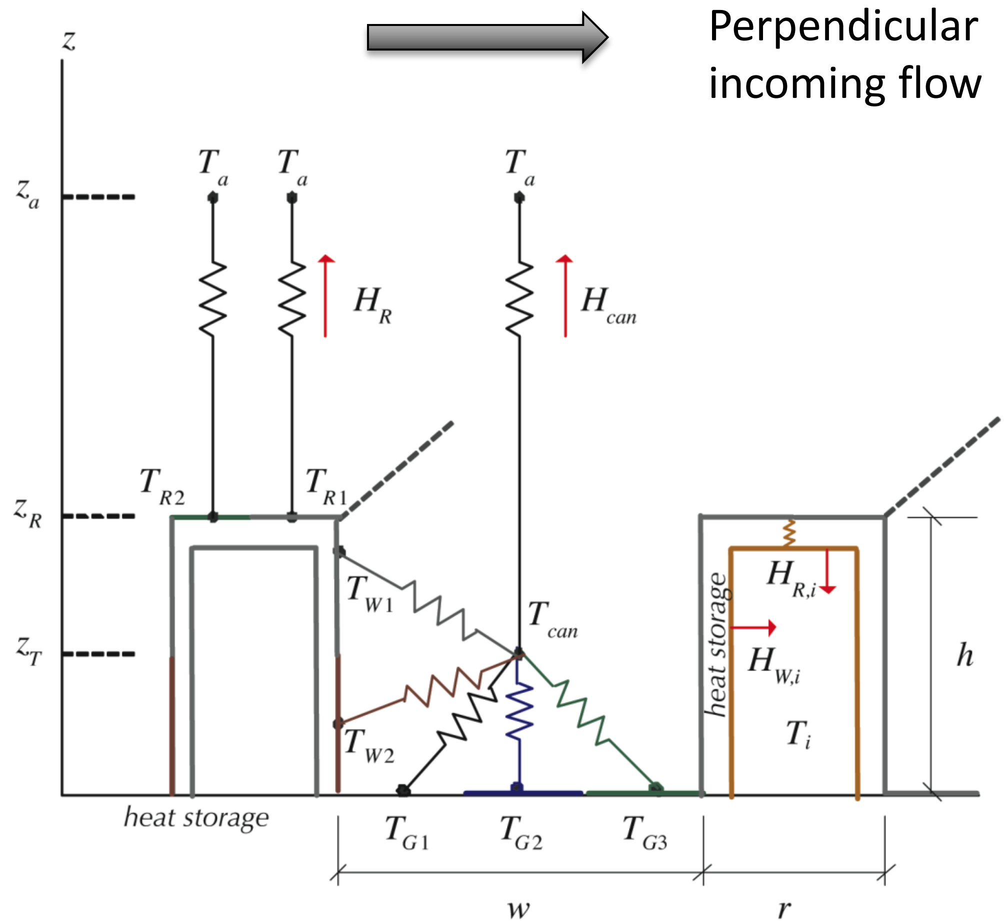
  e.g. shapes, surroundings and surface materials

2. To apply it to real-world problem of interest

UCM: captures urban land surface processes
- Scalable but preferably applied at neighborhood ~ city scale

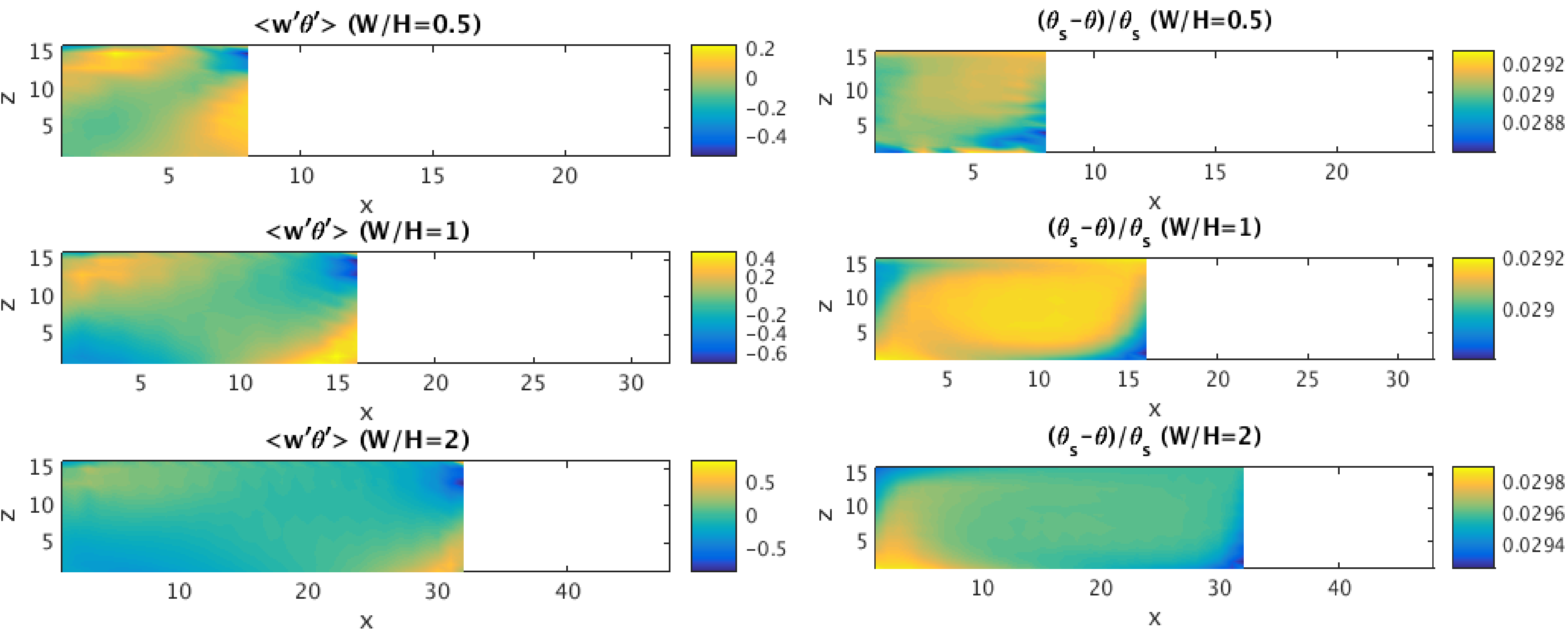
LES: details of flow at building-resolving scale

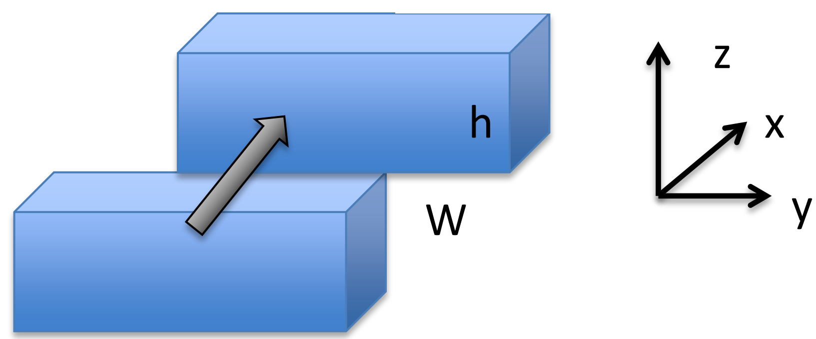
LES can be used to provide physical parameters for transfer processes in UCM



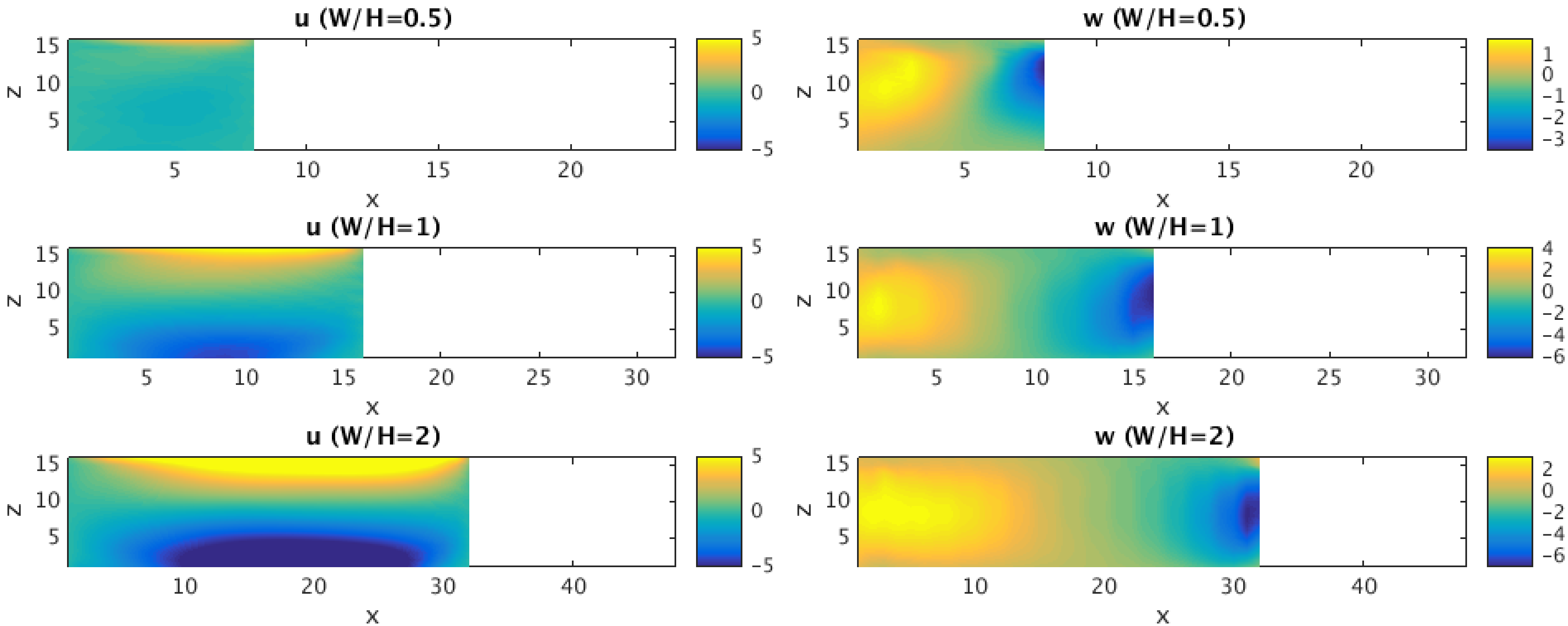
(*Wang et al., 2013*)

Turbulent heat flux and temperature deviation: three different 2D canyon configurations

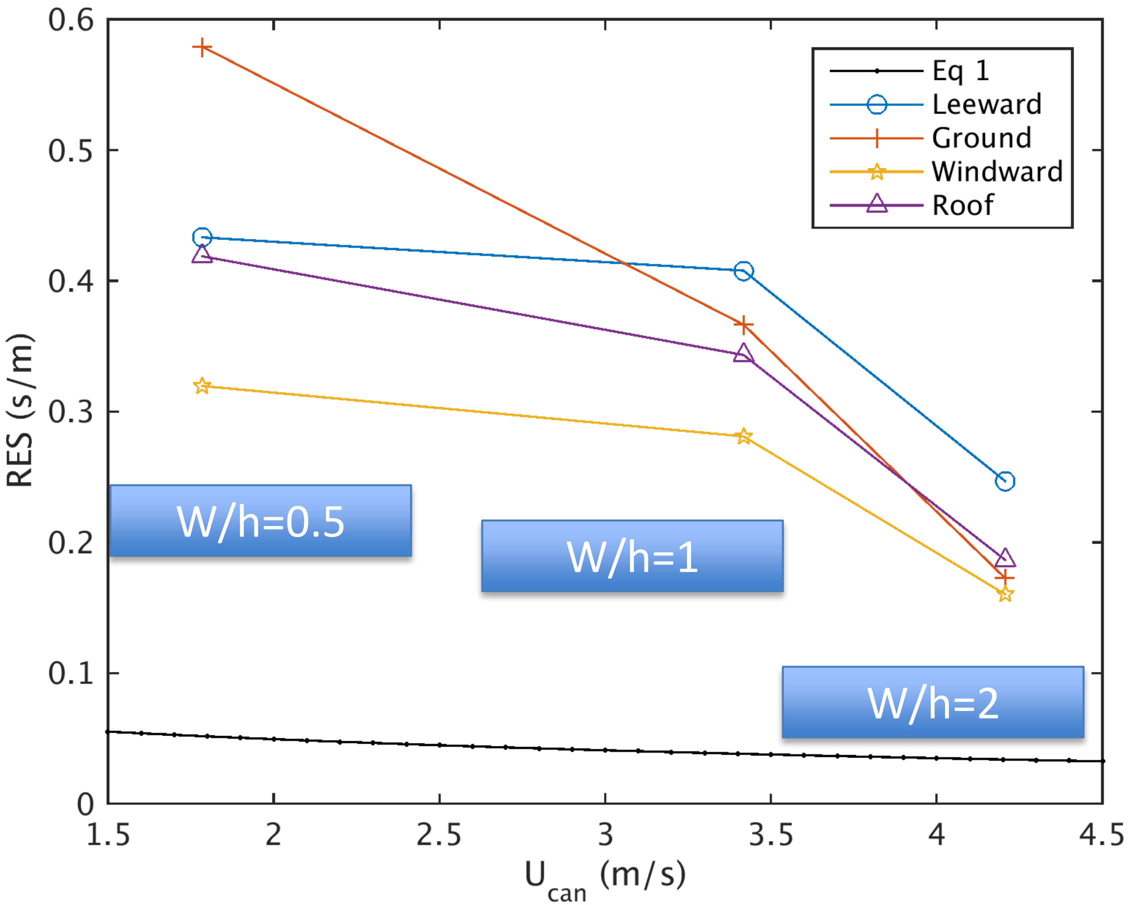




u and w components of wind velocity *inside the canyon*



✧Both *u* and *w* determine the turbulent transfer of heat and scalar.



$$\text{Eq. 1:} \quad RES = \left(11.8 + 4.2U_{can}\right)^{-1}$$

- ✧ *LES results:* different facets perhaps require different treatments, *especially with high aspect ratio configurations*
- ✧ Eq. 1: used in many UCMs, e.g. Masson (2000)
- ✧ Could be an order of magnitude difference in resistance

Conclusion

- ✧Wall-modeled LES captures spatial variation on facets of 2D canyons
- ✧Nu predicted from LES for a single cube is comparable to *laboratory scale* experiment
- ✧For a single cube, extreme h_c occurs on edges
- ✧Bulk *Nu-Re* relation obtained from LES is comparable to *outdoor* experiments
- ✧LES could be used to produce better transfer coefficients for urban land surface model

Future Work

- ✧Derive a better resistance network model for UCM
- ✧Evaluate impact of using different boundary conditions *(i.e. more realistic condition including energy budget constraint)*
- ✧Effect of stability on resistance network model

Acknowledgement

- We thank NCAR **yelllowstone** for our parallel computations