Microscale flow simulations over urban configurations including thermal effects

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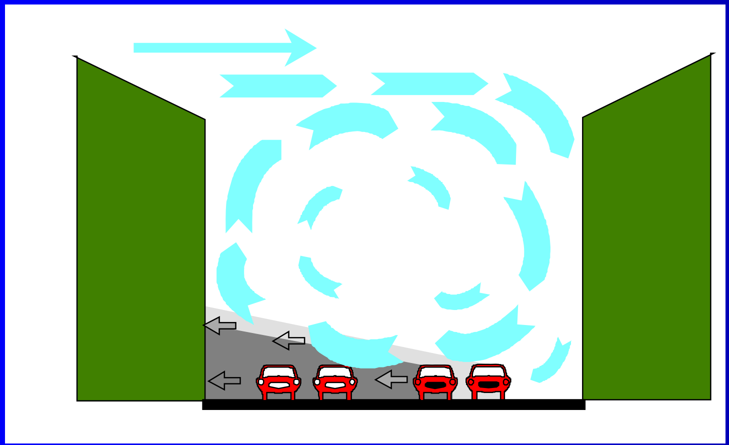
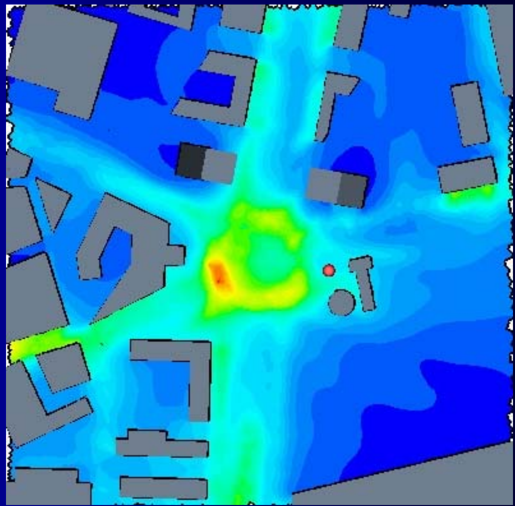
Introduction

- Micrometeorology and pollutant dispersion within cities are important for urban climate, air quality and pedestrian comfort.

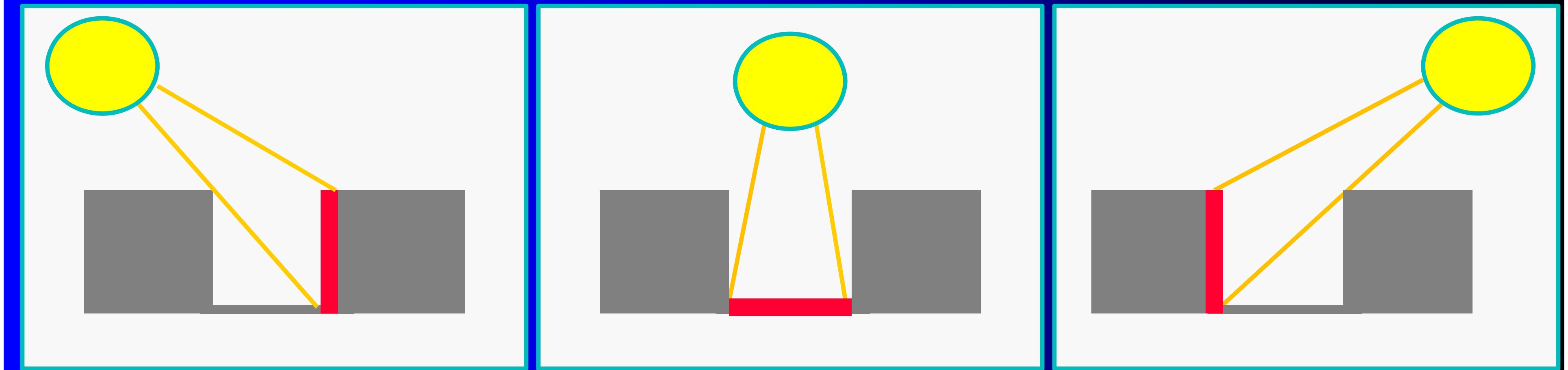
- Interaction between the atmosphere and urban surfaces:
  - Complex flow patterns within the urban canopy
  - Heterogeneous distributions of temperature and pollutant concentration.





Introduction

- One important physical process: Interaction between heat fluxes from building surfaces and streets and the airflow.
- Thermal effects on flow within the canyon are not taken into account by the majority of microscale studies.
- Most scenarios studied (including thermal effects) to date have only heated one wall of the canyon, or the ground.

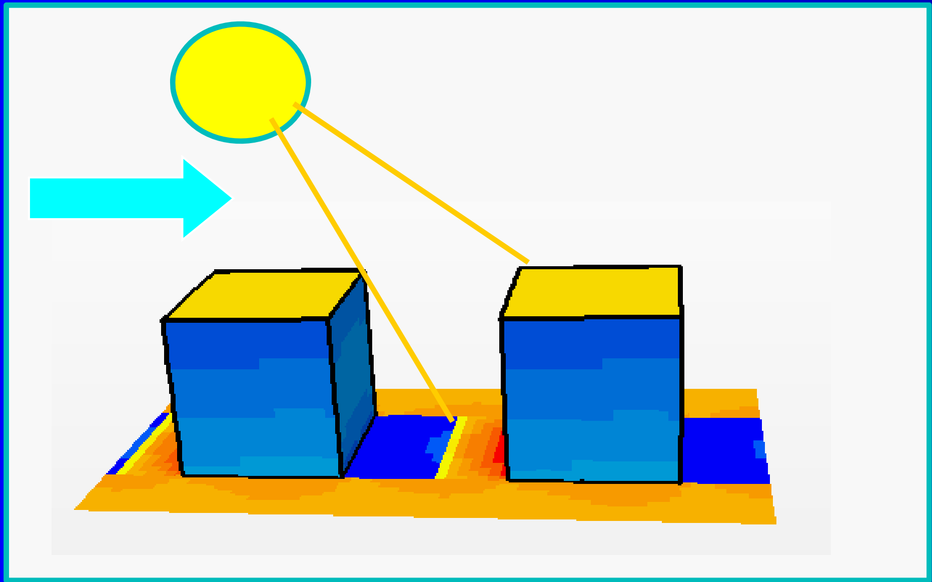


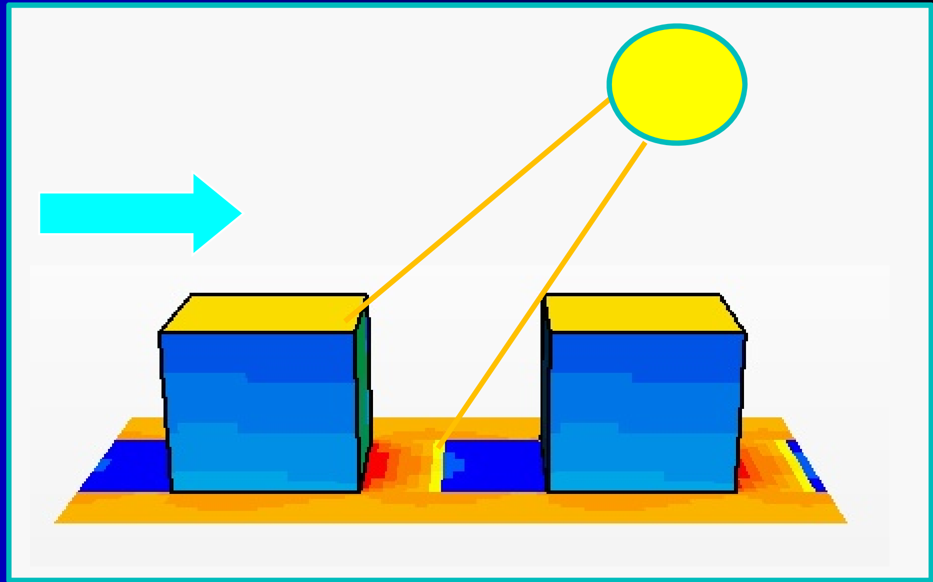
Objective

- To study the impacts of ‘realistic’ distributions of heat fluxes from built surfaces on the airflow through a cube array for a range of ratios of buoyancy to dynamical forces.

Configuration and Set-up

- Array of cubes: lambda= 0.25
- Two solar positions (zenith angle 30º). For each solar position different intensities of heat fluxes are studied.
- CFD simulation using realistic distribution of sensible heat fluxes for each scenario is introduced with high resolution.



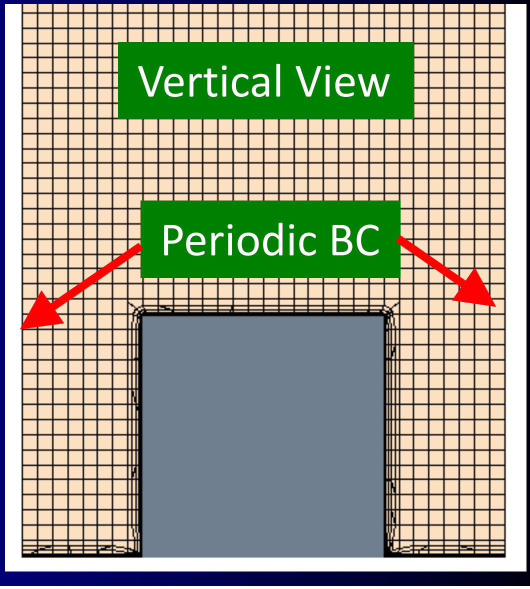


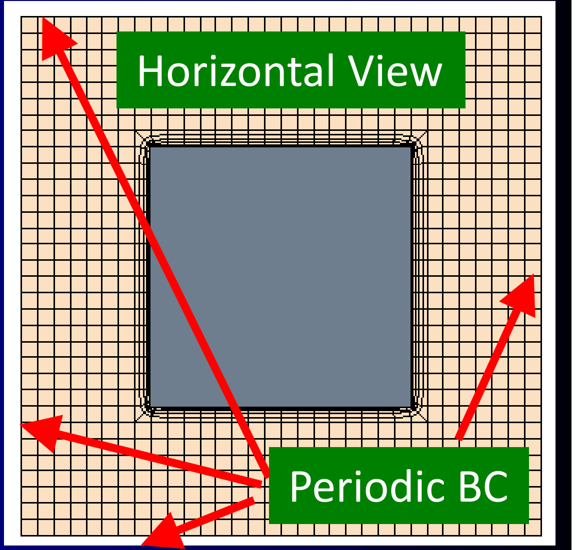
Configuration and Set-up

- Microscale simulation:
- RANS model with k-ε turbulent closure.
- Mesh:
  - Resolution: $h/16$
  - Prism layer close to building walls and ground.
- Periodic domain at horizontal directions
- Boundary conditions:
  - Building and ground: standard wall functions.
  - At the top of the domain (4*h*):
    - a downward flux of momentum ρu_τ^2 in the X-momentum equation is imposed to maintain the flow.
    - Concerning temperature boundary conditions at the top, a *Tref* is fixed allowing a flux equals to

$$k_{eff}\left(T_{ref}-T\right)/\Delta z$$

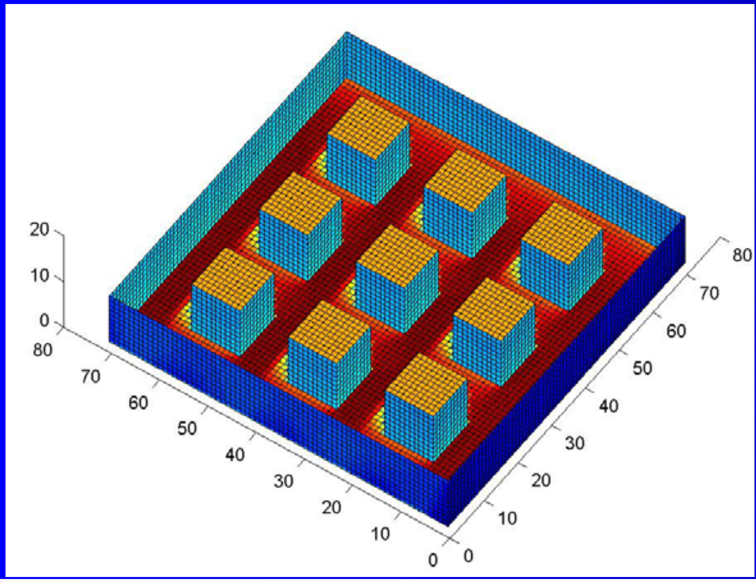
where *keff* is the effective thermal conductivity.

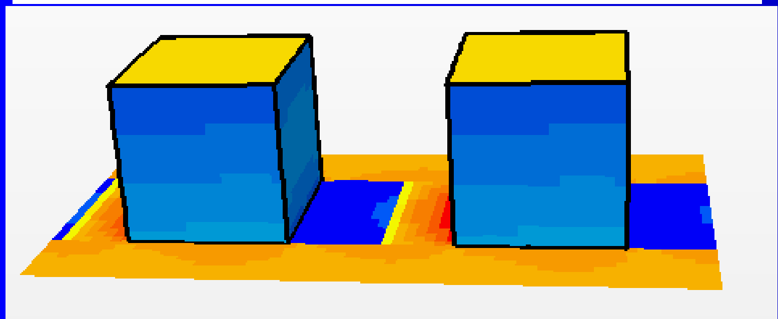




Configuration and Set-up

Boundary conditions for ground and building walls: Microscale 3-D urban energy balance model





- Temperatures of Urban Facets in 3-D (TUF3D) calculates radiative exchange and surface temperature at the patch/sub-facet scale in 3-D.
- The model assumes radiation is the primary driver of the surface temperature distribution.
- TUF3D compares well with surface temperature measurements from Vancouver and Basel.

Krayenhoff E.S. and Voogt J.A. (2007) A microscale three-dimensional urban energy balance model for studying surface temperatures. *Boundary-Layer Meteorol.* 123, 433-461.

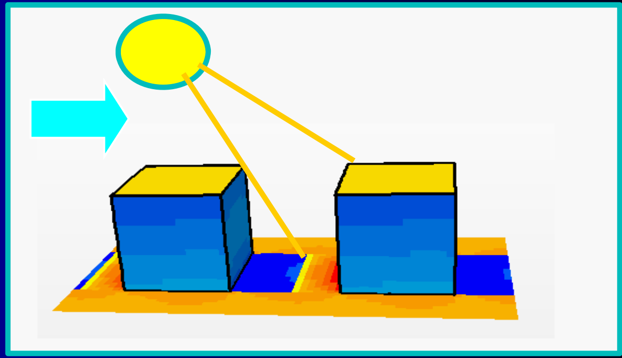
Cases studied

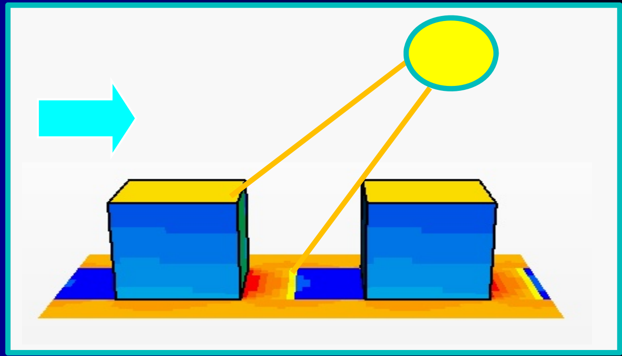
- Two different solar position (30º)
- For each solar position different heat flux intensity. (h/L_{urb}). Analogy with Monin-Obukhov length.

$$L_{urb} = \frac{u_\tau^{\ 3}}{\left(\frac{g}{T_{ref}}\frac{Q_h}{\rho C_p}\right)}$$

- h/L_{urb} = 0, 0.4, 0.75, 1.13, 1.5, 2.25, 3
- Two simulations with the same h/L_{urb} provides equivalent results (***checked***)
- Normalization of velocity with u_τ
- Normalization of temperature:

$$\frac{Q_h / \rho C_p}{u_\tau}$$

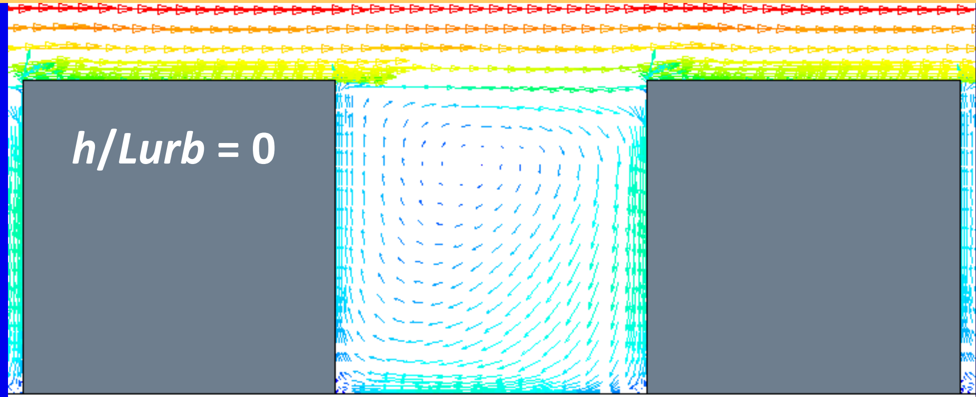




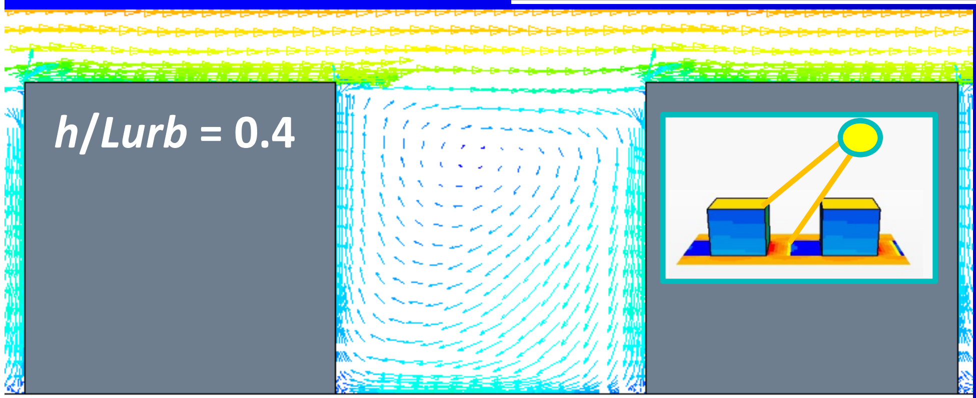
u_τ : related with downward flux of momentum ρu_τ^{2} in the X-momentum equation imposed to maintain the flow.
Qh: is the total heat flux (W m-2) from all urban surfaces,
ρ: is the density of air,
Cp: is the specific heat of air, and
Tref: is a reference temperature (in this case *T* at the top of domain is considered)

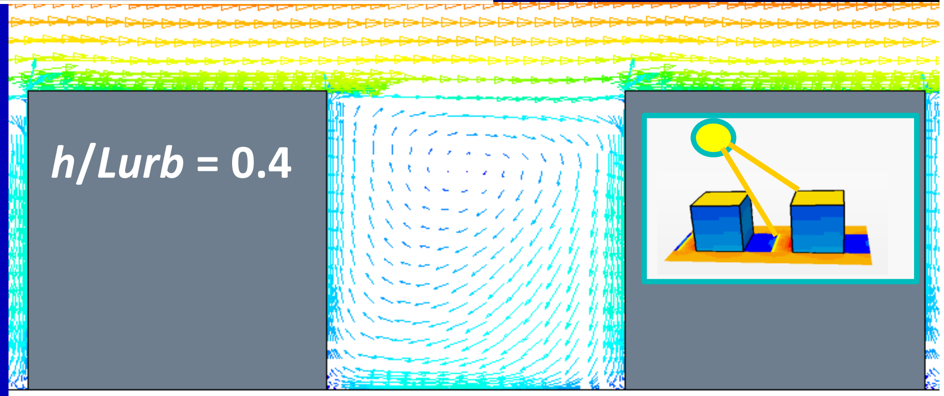
Microscale properties (Temperature normalized)

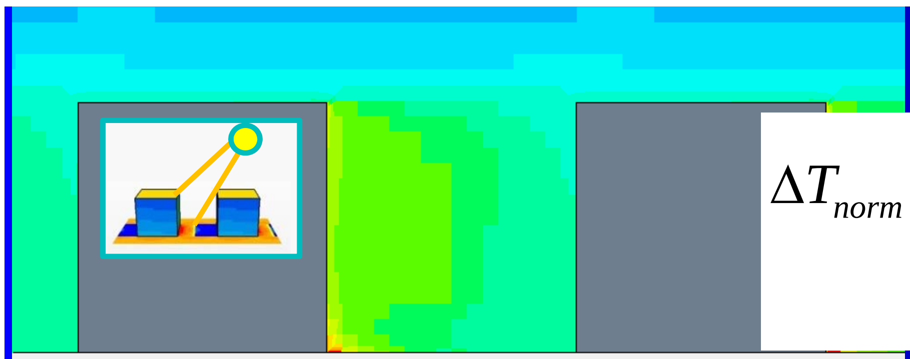
$$L_{urb} = \frac{u_\tau^{\ 3}}{\left(\frac{g}{T_{ref}}\frac{Q_h}{\rho C_p}\right)}$$



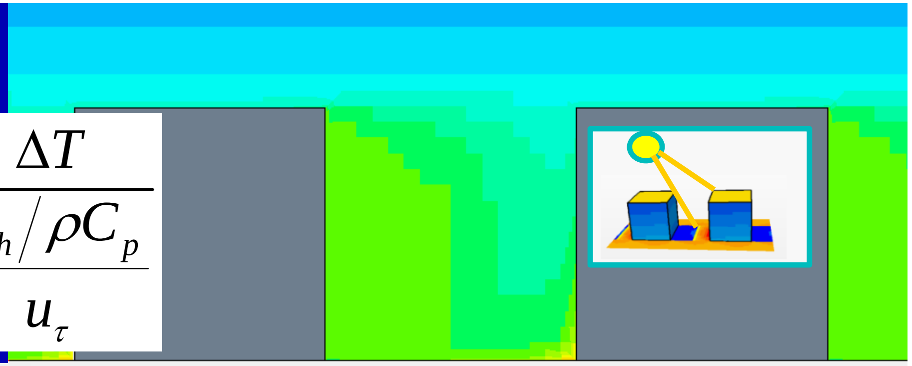
h/Lurb = 0.4

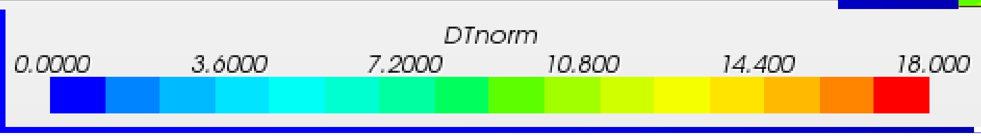






$$\Delta T_{norm} = \frac{\Delta T}{\frac{Q_h/\rho C_p}{u_\tau}}$$

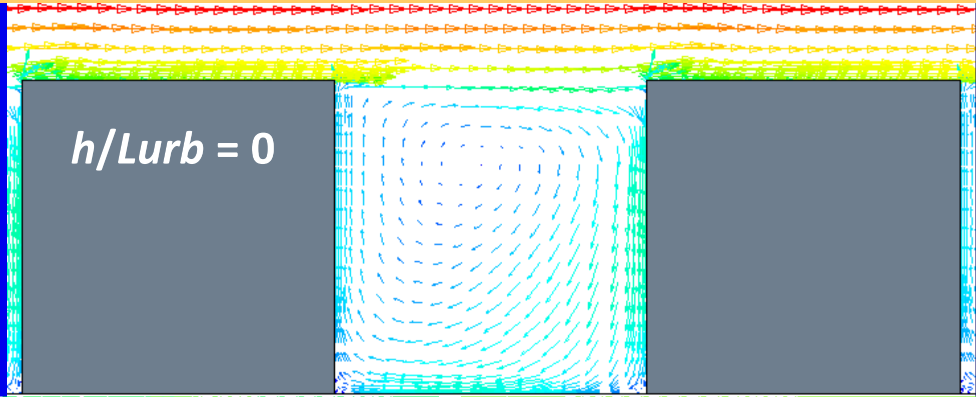




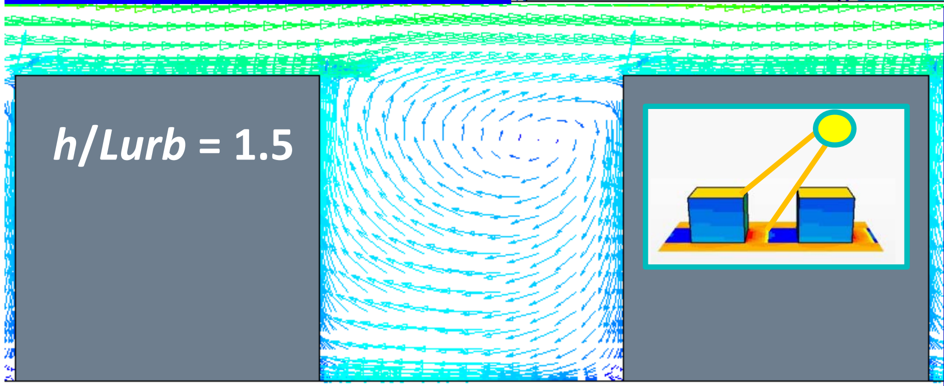
Note: ΔT_{norm} is proportional to $1/Q_h$

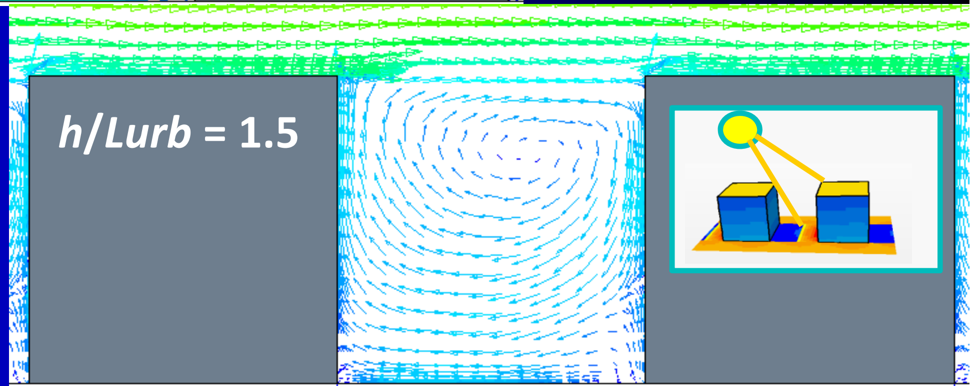
Microscale properties (Temperature normalized)

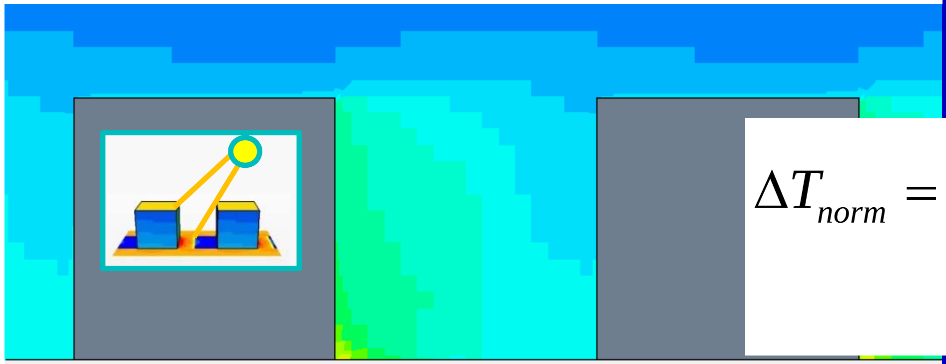
$$L_{urb} = \frac{u_\tau^{\,3}}{\left(\dfrac{g}{T_{ref}}\,\dfrac{Q_h}{\rho C_p}\right)}$$

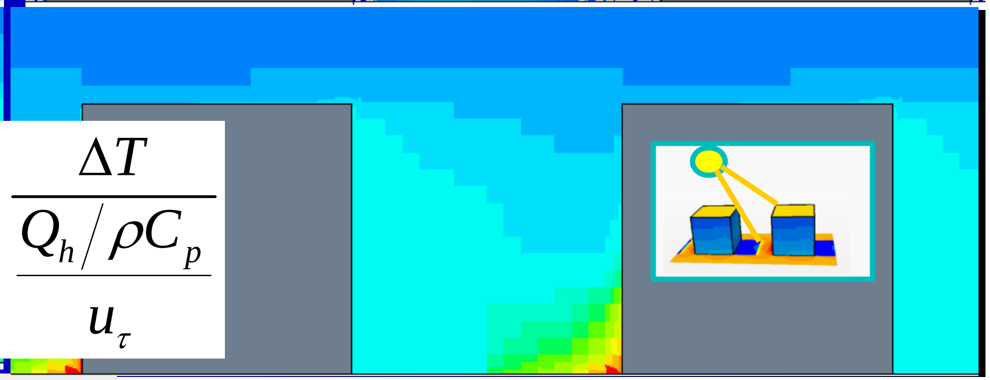


h/Lurb = 1.5







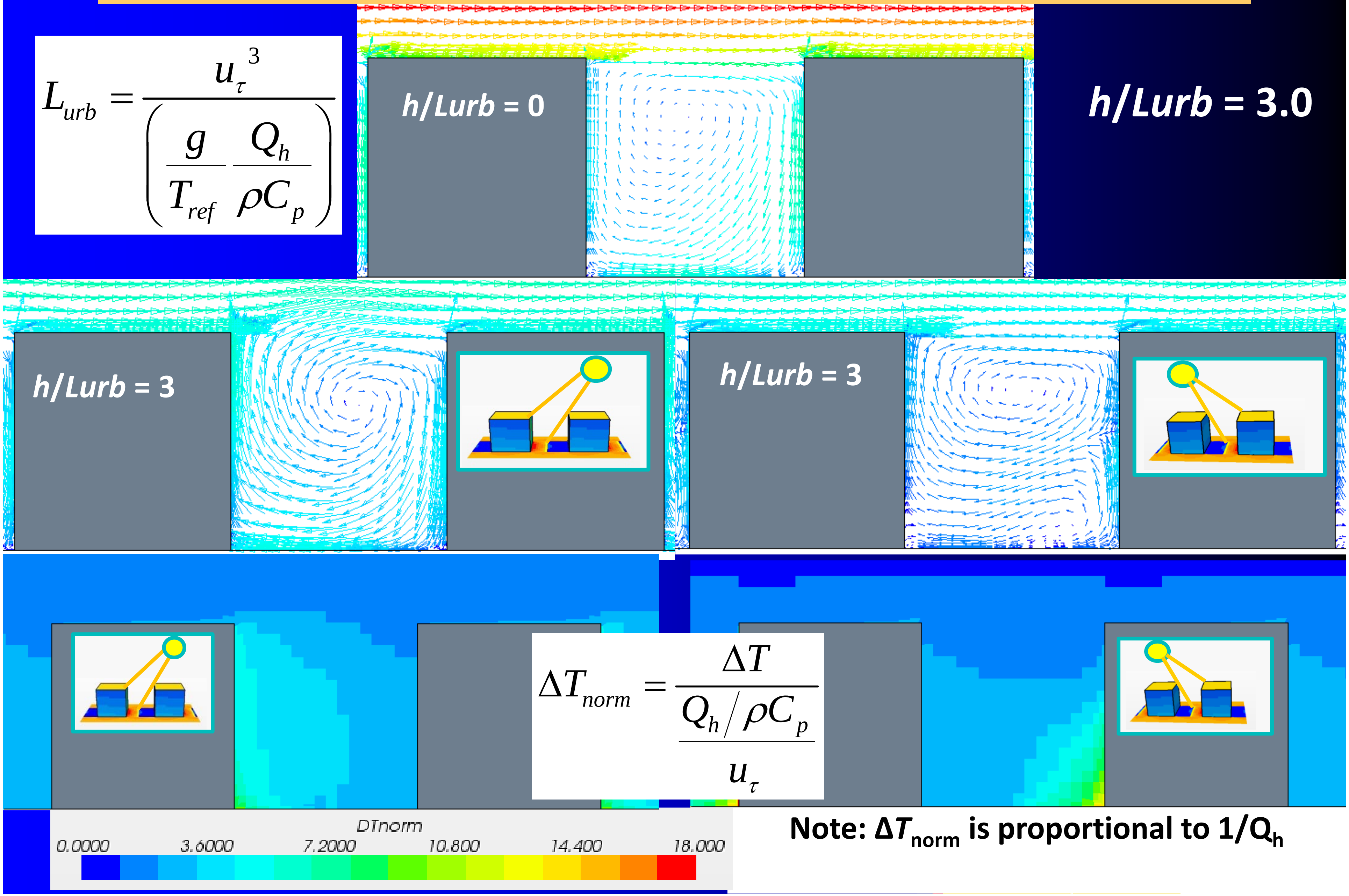


$$\Delta T_{norm} = \frac{\Delta T}{\dfrac{Q_h/\rho C_p}{u_\tau}}$$

Note: ΔT_{norm} is proportional to $1/Q_h$

Microscale properties (Temperature normalized)

$$L_{urb} = \frac{u_\tau^{\,3}}{\left(\frac{g}{T_{ref}}\frac{Q_h}{\rho C_p}\right)}$$



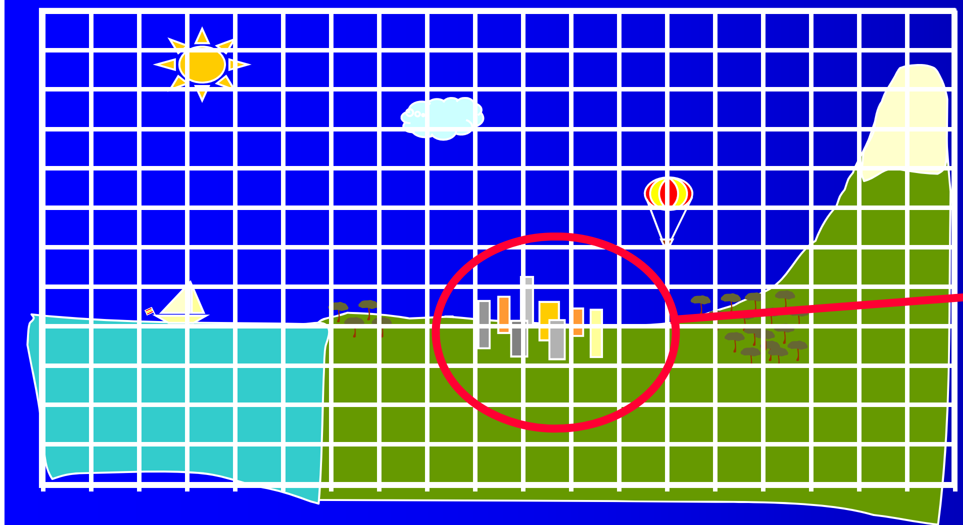
$$\Delta T_{norm} = \frac{\Delta T}{\frac{Q_h / \rho C_p}{u_\tau}}$$

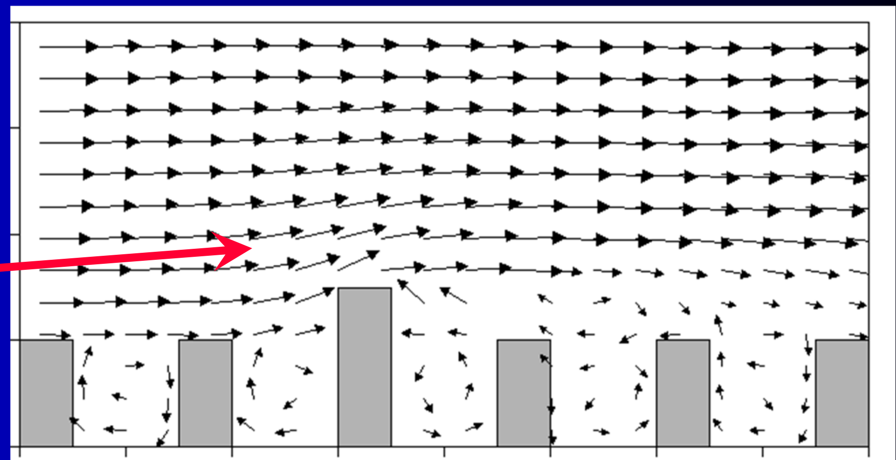
Note: ΔT_{norm} is proportional to $1/Q_h$

Spatially average flow properties

- CFD → High resolution information → Numerical domain cannot cover the whole city

- Mesoscale models → Urban Canopy Models (compromise between simplicity and accuracy) to parameterize processes at smaller scale than mesoscale resolution (i.e. parametrization of drag forces induced by buildings).





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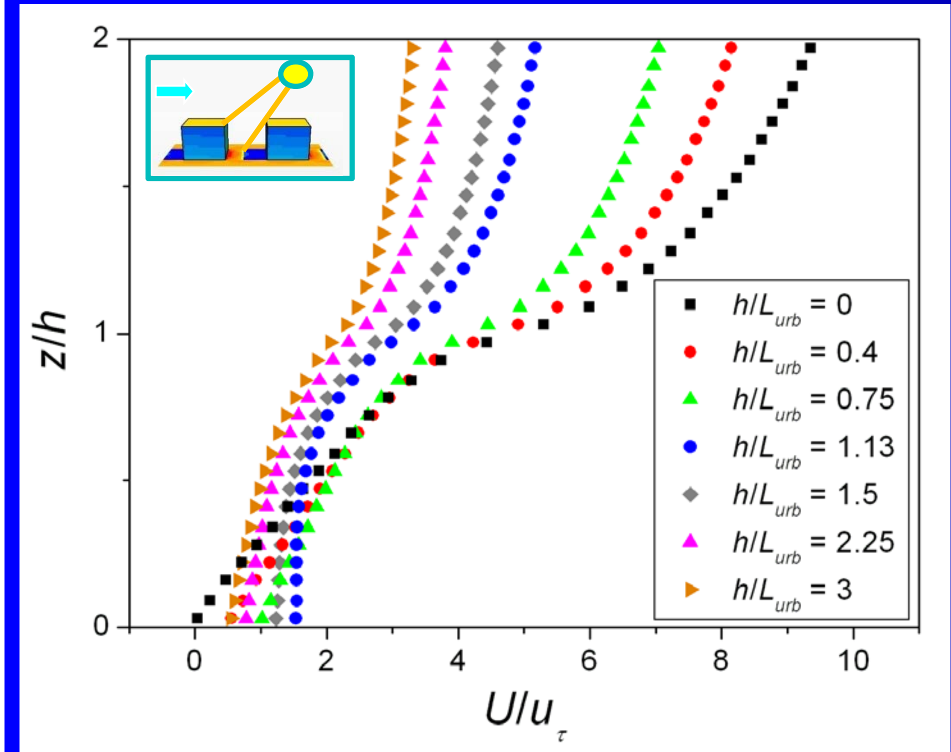
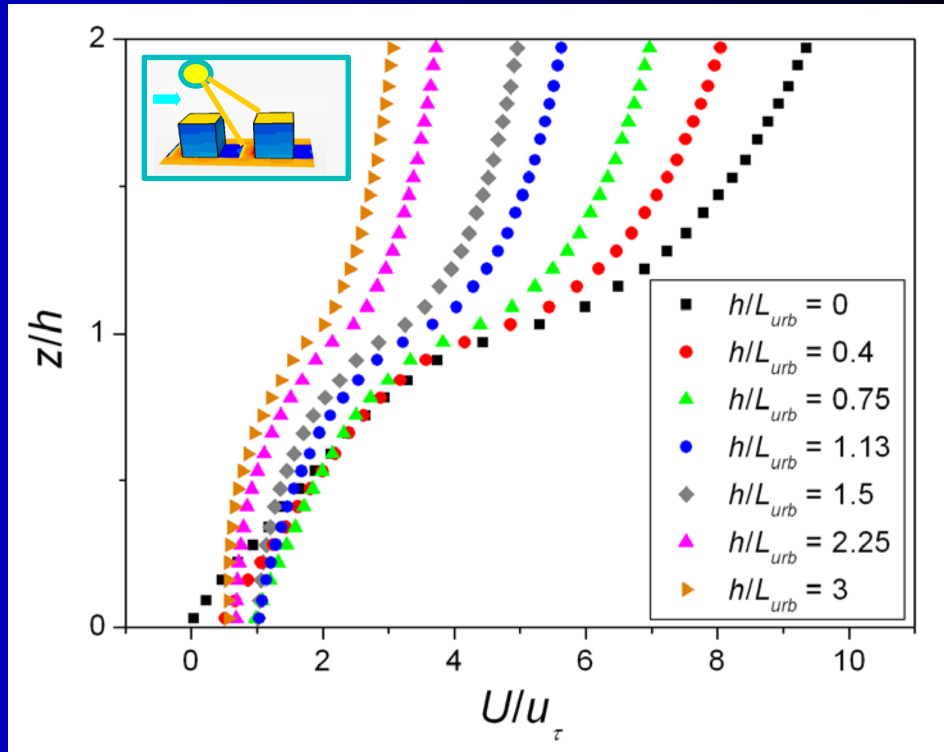
Spatially average flow properties

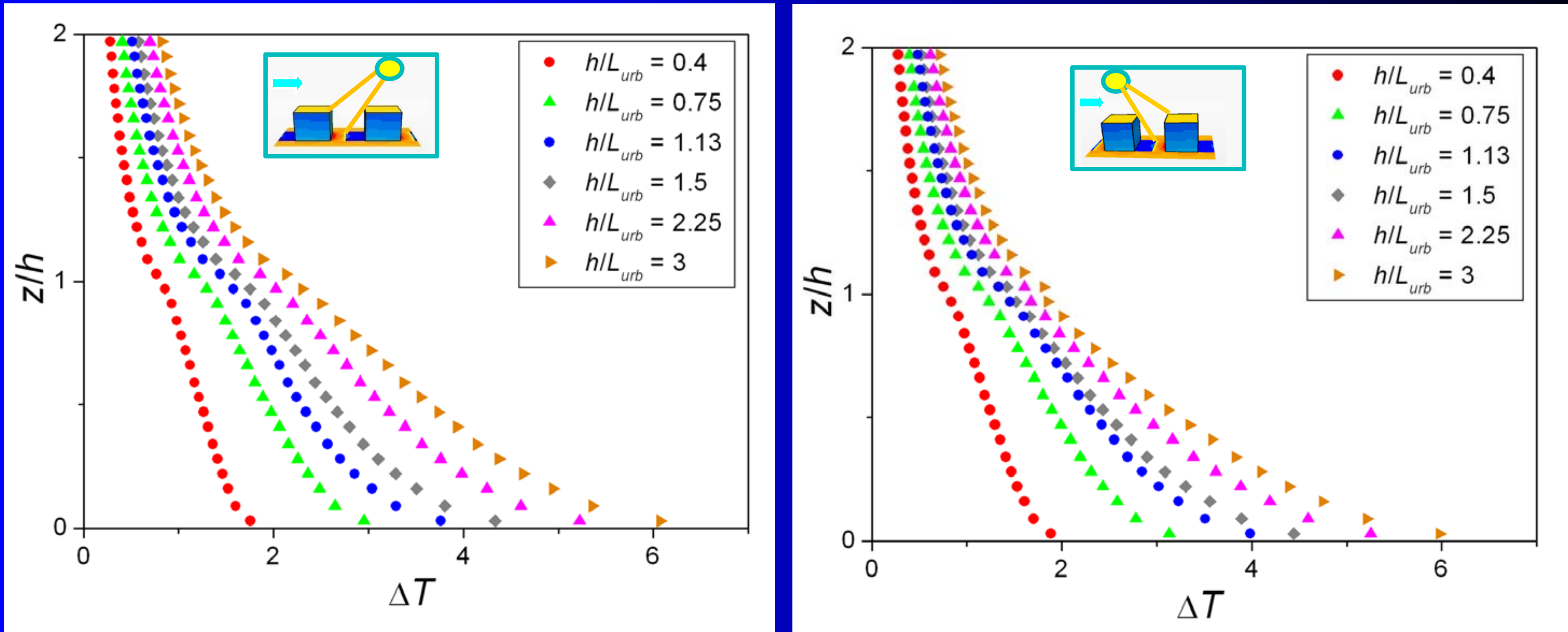
- Flow





Spatially average flow properties

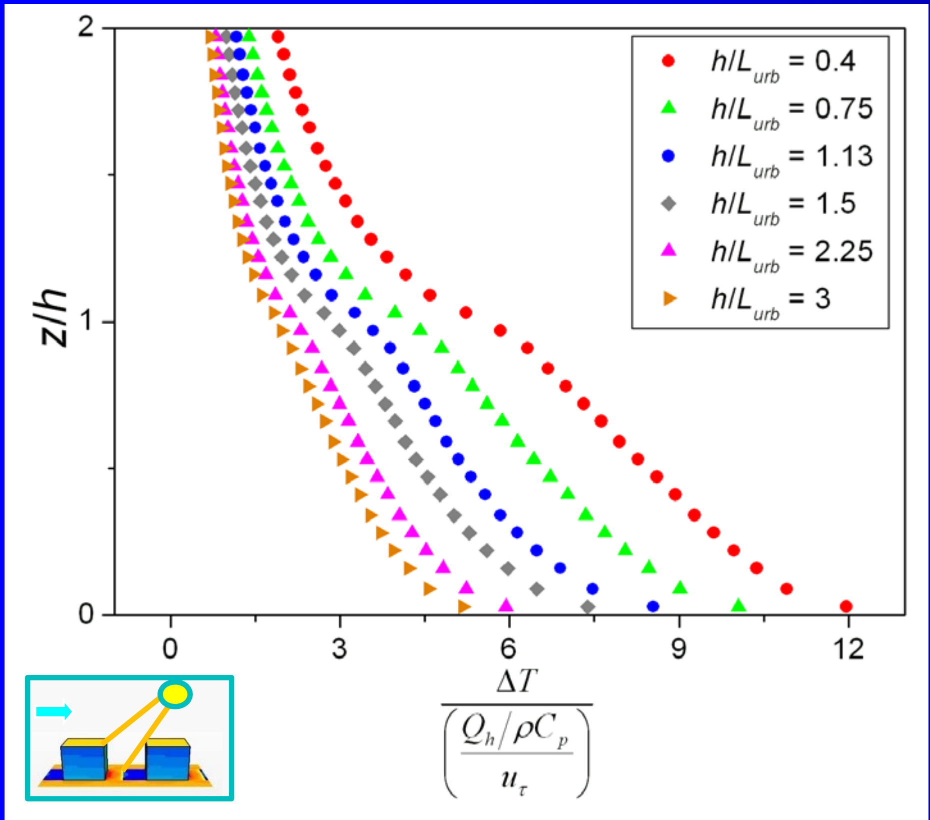
- Temperature ($\Delta T = T - T_{topdomain}$)

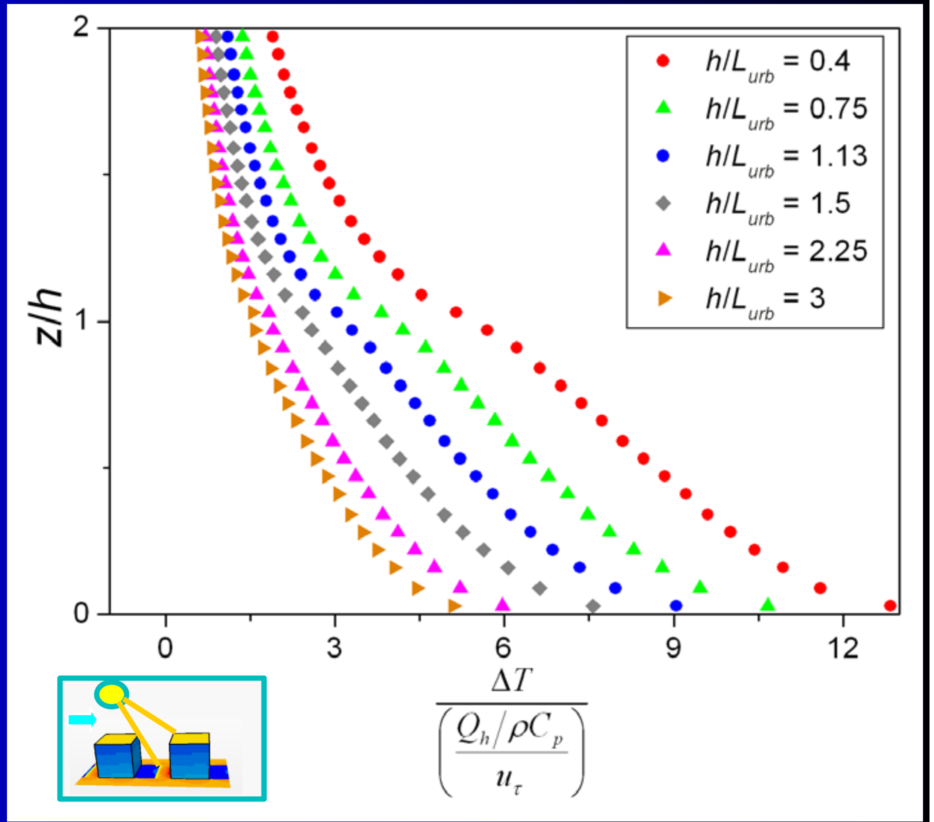


Note: ΔT maps, Q_h varies while u_τ is kept constant.

Spatially average flow properties

- Normalized Temperature $$\Delta T_{norm} = \frac{\Delta T}{\frac{Q_h / \rho C_p}{u_\tau}}$$

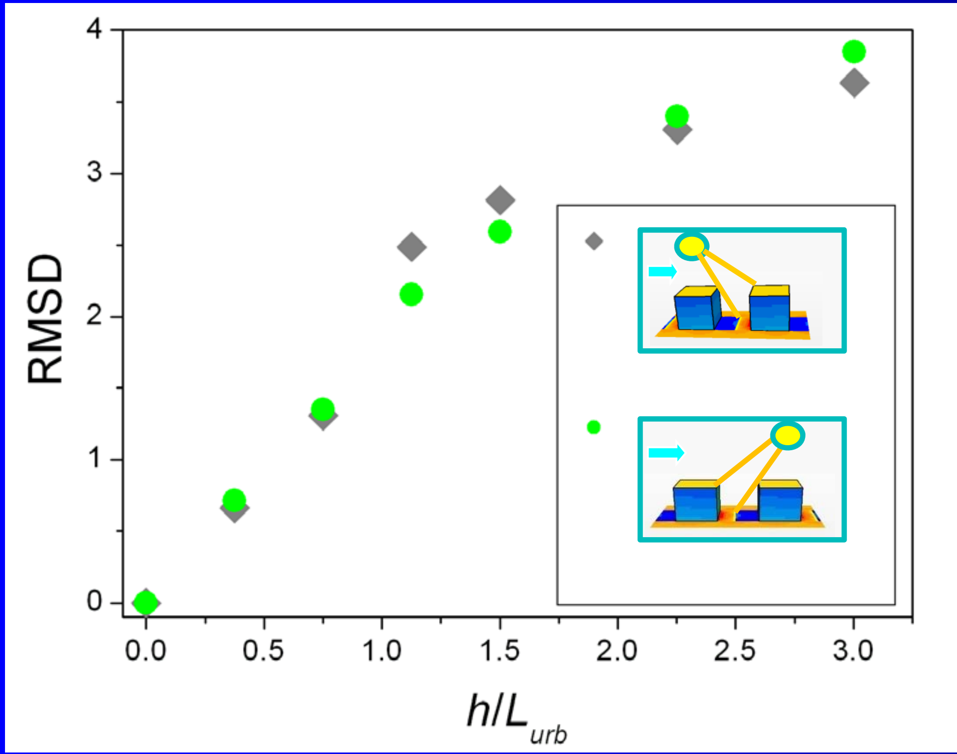




Note: In the normalization ΔT is divided by Q_h .

Spatially average flow properties

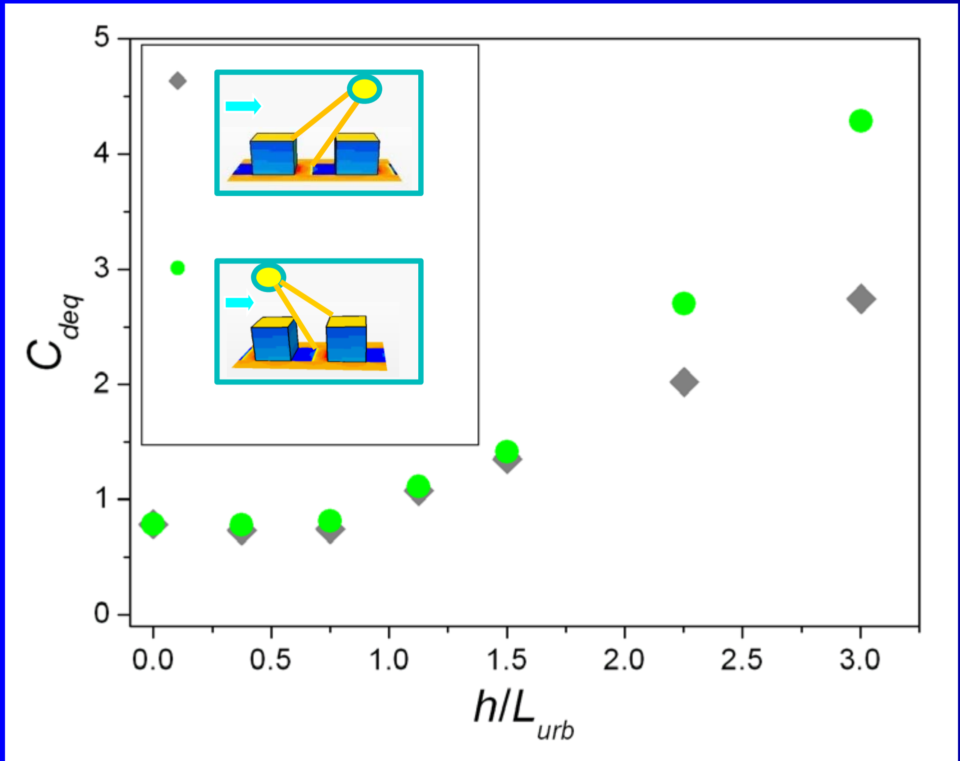
- **Root Mean Square Differences** are calculated for average streamwise velocity profiles, with the neutral case (Qh = 0) as reference.



$$RMSD = \left(\frac{\sum_{1}^{n} \left(U(z) - U_{neutral}(z) \right)^2}{n} \right)^{0.5}$$

Spatially average flow properties

- Drag Coefficient (Urban canopy model)



$$\overrightarrow{Drag}(z) = -\rho S(z) C_d |U| \vec{U}$$

- $S(z)$ is the vertical surface building density (facing the wind), C_d is drag coefficient.

$$C_{deq} = \frac{\int_0^H \Delta P dz}{\rho \int_0^H U^2 dz}$$

- Drag force integrated in the whole canopy is equal to that computed by RANS simulations.

Summary and Conclusions

- Scenarios with realistic heat fluxes imposed at the ground and at the roof and walls of buildings are simulated by a CFD model.
- Two solar positions and different intensities of heat fluxes (variation of *h/Lurb*) for each position are simulated.

$$L_{urb} = \frac{u_\tau^{\ 3}}{\left(\frac{g}{T_{ref}} \frac{Q_h}{\rho C_p} \right)}$$

- For both solar position for *h/Lurb* ≥ 1.13 flow pattern changes notably respect to neutral case. Different flow regimes.
- Different flow regimes depending on solar position (for the same *h/Lurb*), especially for *h/Lurb* ≥ 1.13.

↓

- Differences in temperature maps inside the canyons. Location of the maximum at different side of the street.

Summary and Conclusions

- Variation of spatially average velocity and temperature profiles with *h/Lurb*.

- Spatially average velocity and temperature profiles are similar for both solar position for the same *h/Lurb.*

- Drag coefficient (*Cdeq*) useful for urban canopy models (UCP).

  - Cdeq similar to neutral case for *h/Lurb* ≤ 0.75.

  - Cdeq increases substantially for *h/Lurb* ≥ 1.13 (high buoyancy force) → this effect should be important to include in parameterization of drag in UCP.

- In future work, cases with different solar angles will be analysed in order to generalise these results.

Thank you for your attention