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The role of thermal convection in the dispersion of traffic-induced air pollutants in the urban environment

Bálint PAPP
papp@ara.bme.hu
Department of Fluid Mechanics,
Budapest University of Technology and Economics

Gergely KRISTÓF
kristof@ara.bme.hu
Department of Fluid Mechanics,
Budapest University of Technology and Economics

Model essentials

Periodic geometry

- Periodic BCs at all lateral boundaries (x and y)
- Small domain: high resolution + high speed
- The max. size of flow structures is restricted

Atmospheric wind

- Large-scale eddies: sudden changes in wind direction and magnitude
- Control term to include the effect of macroscale fluctuations in the small simulation domain

Solar radiation and natural convection

- Bulk Richardson number:

$$Ri_b = \frac{gL\beta(T_{wall} - T_0)}{U_{ref}^2}$$

- Control term to eliminate artificial heating

Traffic-related air pollution

- Multiple, time-dependent emissions
- Not periodic: pollutants can be dispersed beyond the physical boundaries of the domain

Transient Wind Forcing

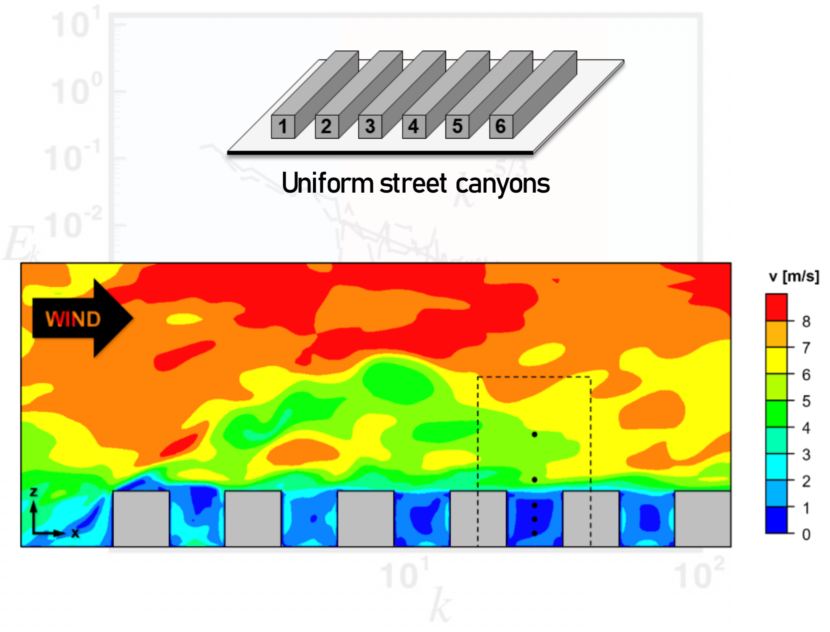
Kristóf, G., Papp, B., Wang, H., & Hang, J. (2020). Investigation of the flow and dispersion characteristics of repeated orographic structures by assuming transient wind forcing. Journal of Wind Engineering and Industrial Aerodynamics, 197, 104087.

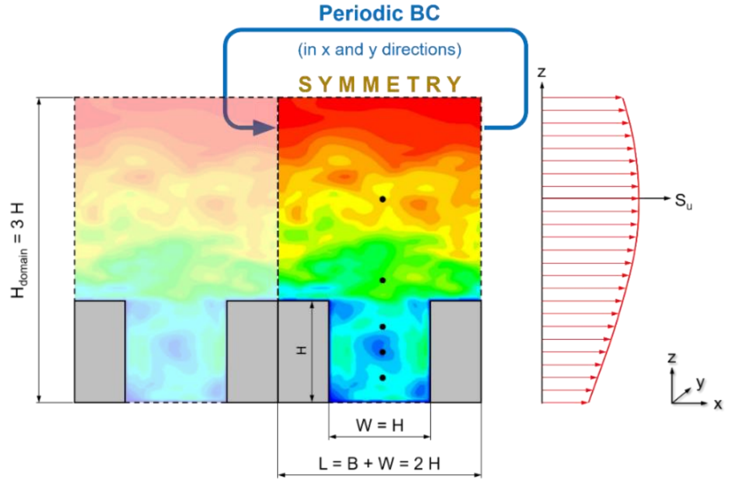
Turbulent scales can be divided into…

- Macroscopic turbulence:
  - ➢ Flow structures larger than the domain size
  - ➢ Rapid changes in wind direction and magnitude
  - ➢ Imposing measured u(t) and v(t) time series at the reference location within the periodic domain
    - Transient Wind Forcing method: volume source of momentum

$$S_u(z,t) = \rho \cdot a(t) \cdot G(z) = \rho \cdot \frac{u_{meas}(t) - u_{CFD}(t)}{\tau(t)} \cdot e^{-\frac{1}{2}\left(\frac{z - z_{ref}}{L_0}\right)^2}$$

    - Proportional control (flow-through time): minimizing the difference between measurement and simulation data
- Mesoscopic turbulence: unsteady velocity field (LES)
- Microscopic (unresolved) turbulence: captured by the sub-grid-scale stress (SGS) model
  - ➢ Smagorinsky-Lilly model (C_s = 0.1)

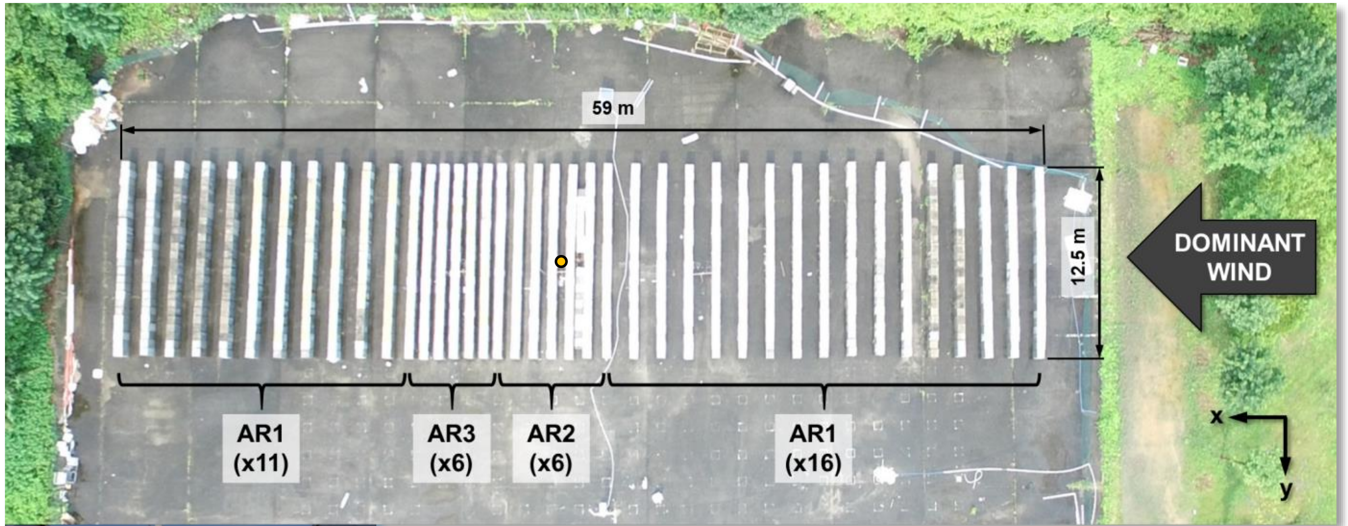


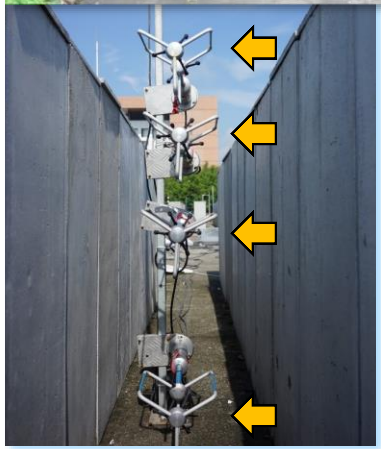


Validation of the TWF model

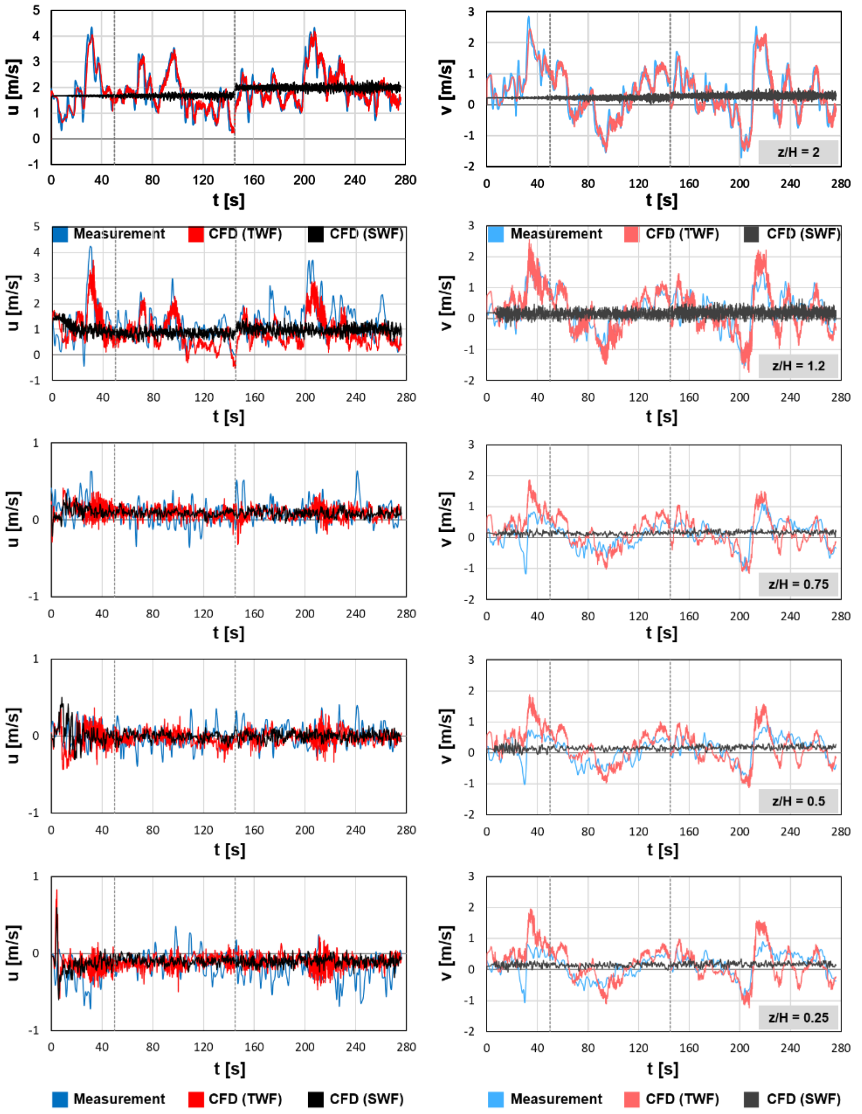
Kristóf, G., Papp, B., Wang, H., & Hang, J. (2020). Investigation of the flow and dispersion characteristics of repeated orographic structures by assuming transient wind forcing. Journal of Wind Engineering and Industrial Aerodynamics, 197, 104087.

Field measurements: u(t) and v(t) time series at z = 2H = 2.4 m, over the street canyons (SYSU, China) → CFD model





- Comparison at 4 further gauging points below the reference location
  - ➢ Time average
  - ➢ Fluctuations
- The 3D turbulent flow field is reproduced with sufficient accuracy

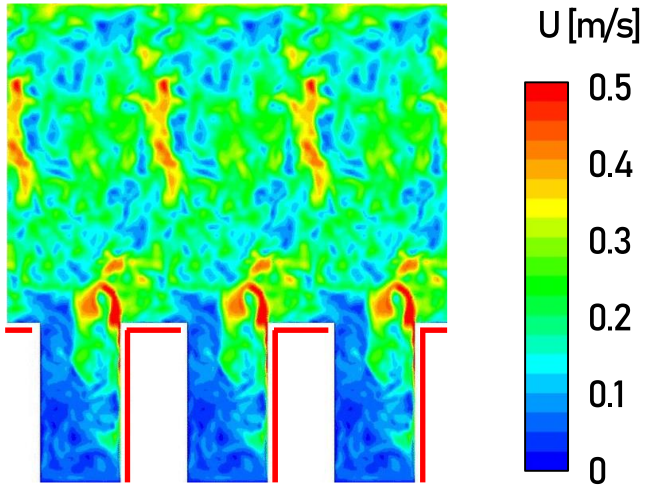


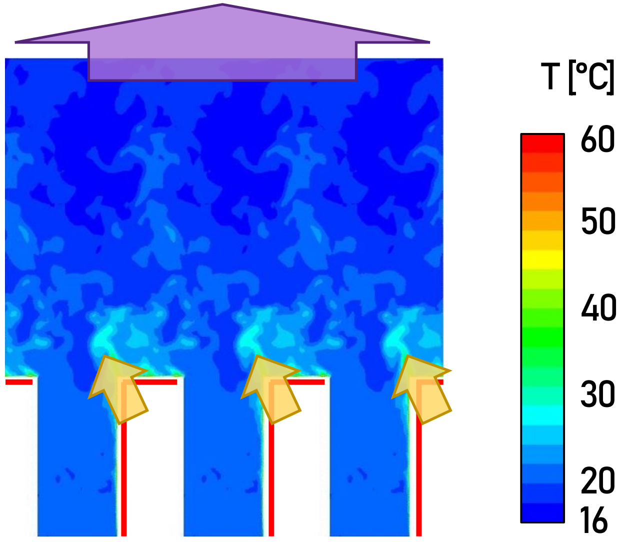
Temperature control

- Lower region of the atmospheric boundary layer
  - ➢ Strong turbulent mixing
  - ➢ Equilibrium of the sensible heat fluxes: $Q_{wall} = Q_{upper}$
- Constant average/bulk temperature
  - ➢ The heat introduced by the hot walls must be consumed by sinks

$$S_T(\vec{x},t) = -\rho_0 c_v \cdot \frac{T_{avg}(t) - T_0}{\Delta x} \cdot \left[\vec{v}(\vec{x},t) \cdot \overrightarrow{d_0}\right]$$

  - ➢ Patankar et al. (1977): streamwise periodic, steady-state model for heat exchangers → extension to 2-way periodicity (XY)
  - ➢ Wind direction: time average or instantaneous
- The vertical temperature distribution is not modified, only shifted
  - ➢ Initial (reference) temperature: $T_0 = 20\ [°C] > T_{min}$

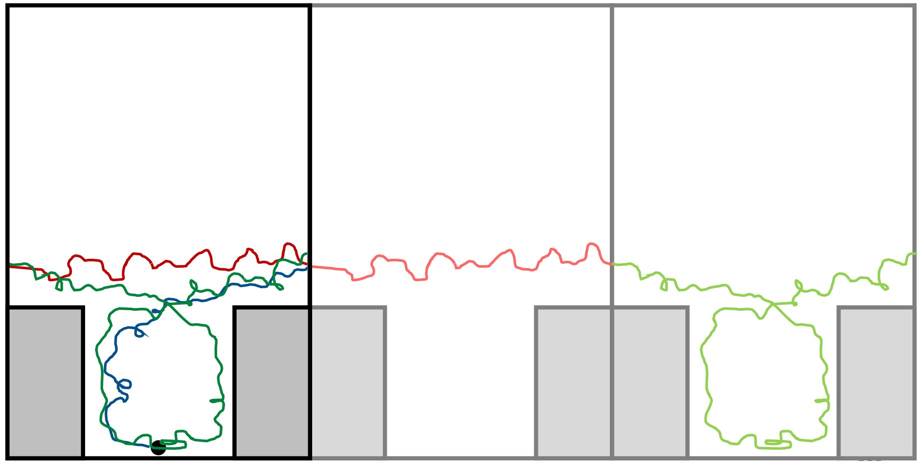




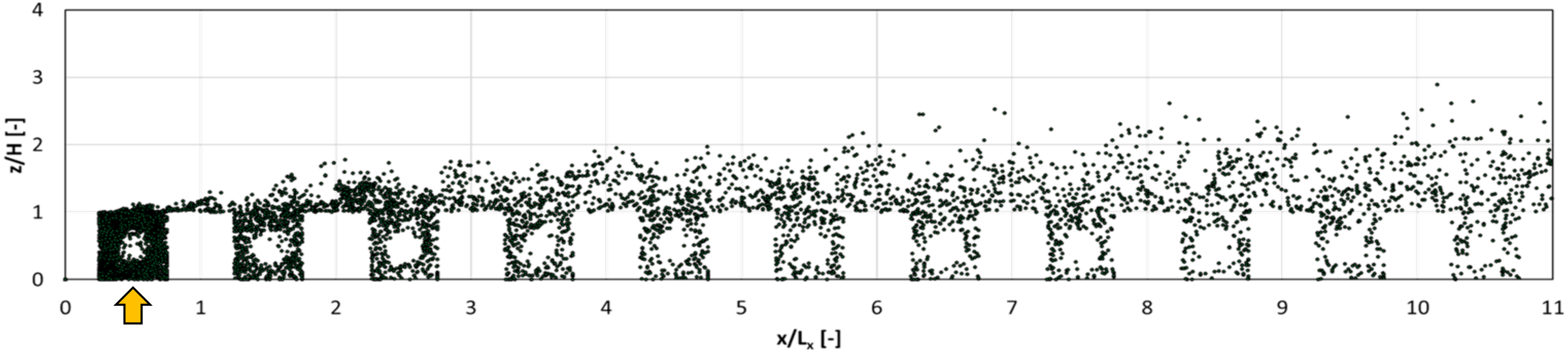
Patankar, S. V., Liu, C. H., & Sparrow, E. M. (1977). Fully developed flow and heat transfer in ducts having streamwise-periodic variations of cross-sectional area. Journal of Heat Transfer, 99 (2)

Far-field dispersion

Lagrangian particle tracking + counting the periodic jumps = far-field dispersion

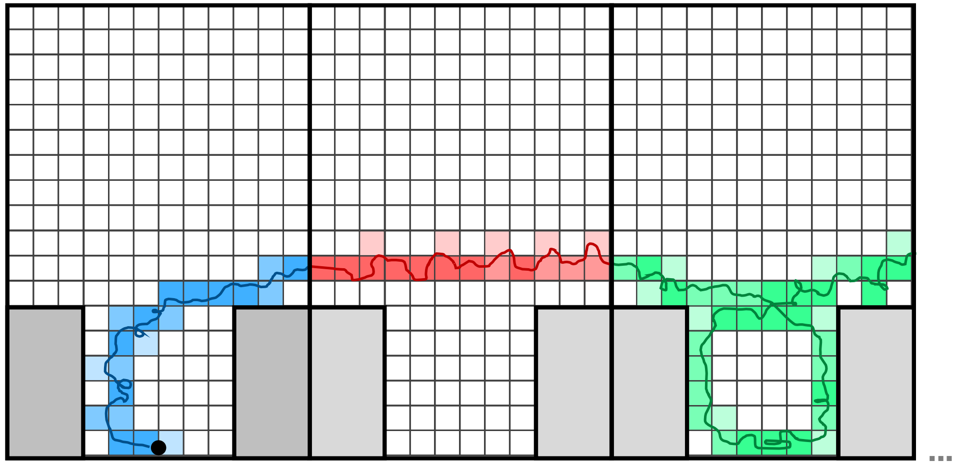


Instantaneous particle plume, emitted continuously from a single point source:



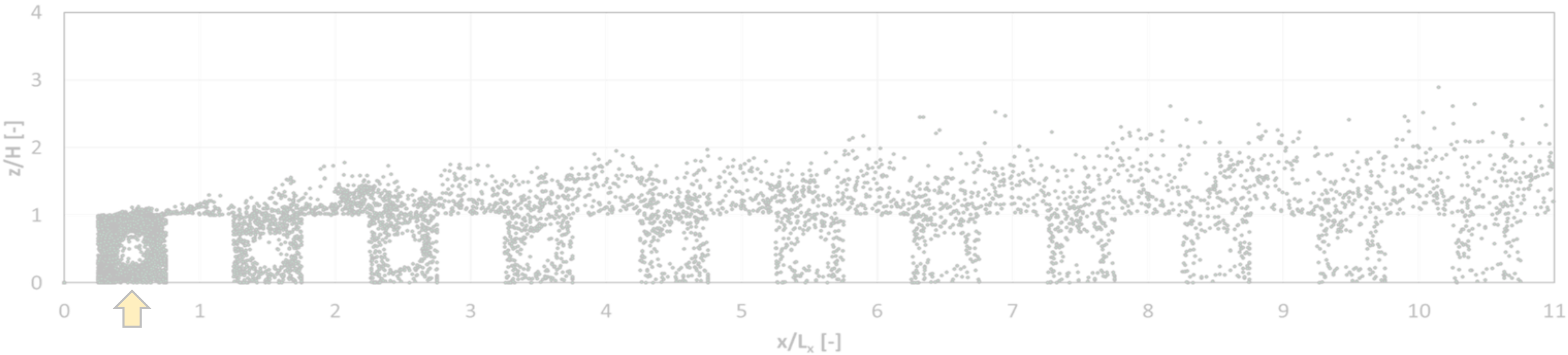
Dose field

Dose field – recording the particles' footprints:



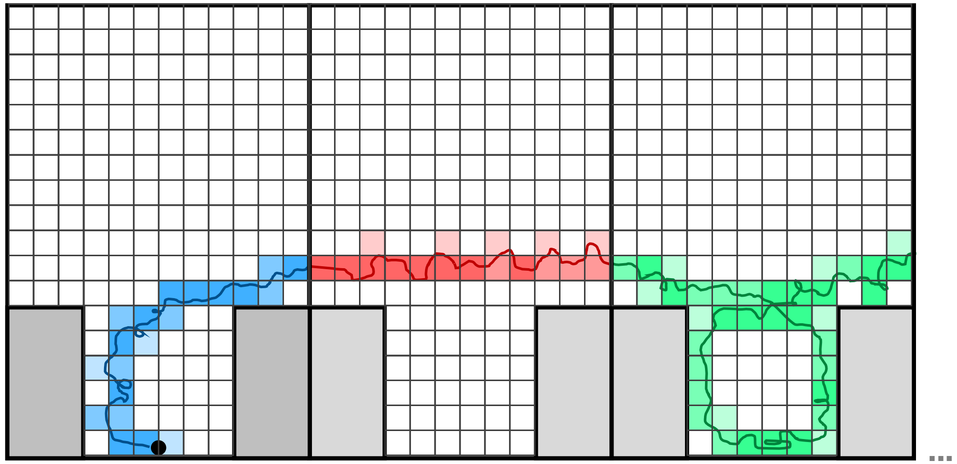
- User Defined Memory fields (ANSYS Fluent)
- Incrementing the cell values by $\Delta t_{particle}/V_{cell}$
- Dose: $$d = \int c \, dt$$
- The dispersion results are validated with data from wind tunnel measurements

Instantaneous particle plume, emitted continuously from a single point source:



Papp, B., Kristóf, G., Istók, B., Koren, M., Balczó, M., Balogh, M. (2021). Measurement-driven Large Eddy Simulation of dispersion in street canyons of variable building height. Journal of Wind Engineering and Industrial Aerodynamics, 211, 104495.

Dose field – recording the particles' footprints:



- User Defined Memory fields (ANSYS Fluent)
- Incrementing the cell values by $\Delta t_{particle}/V_{cell}$
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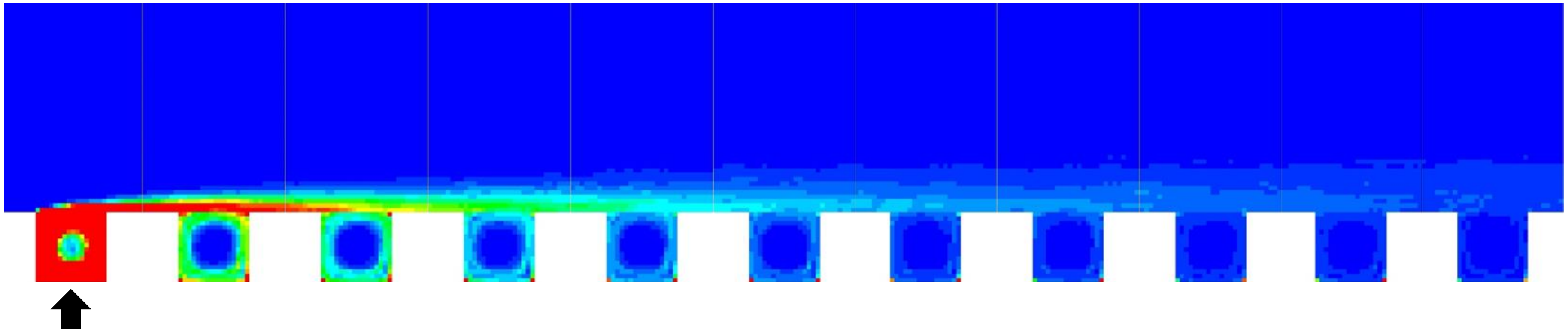
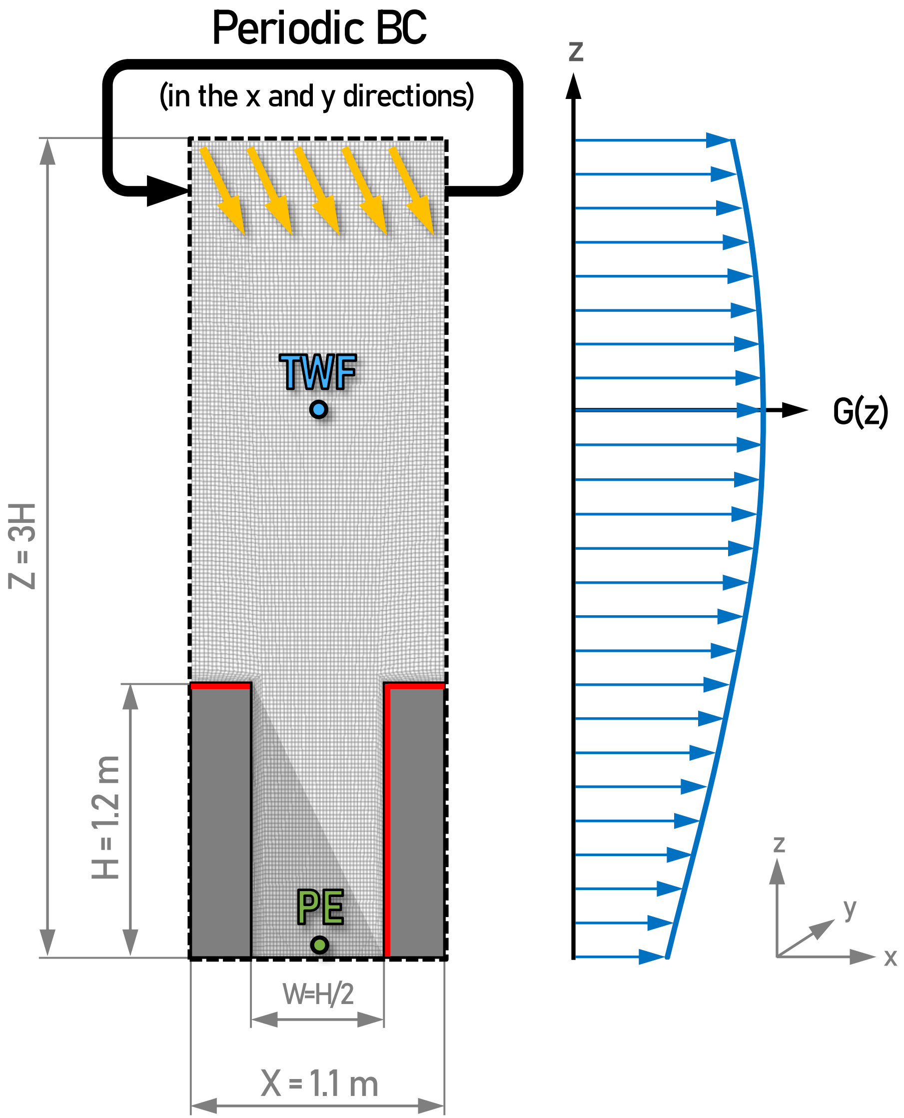
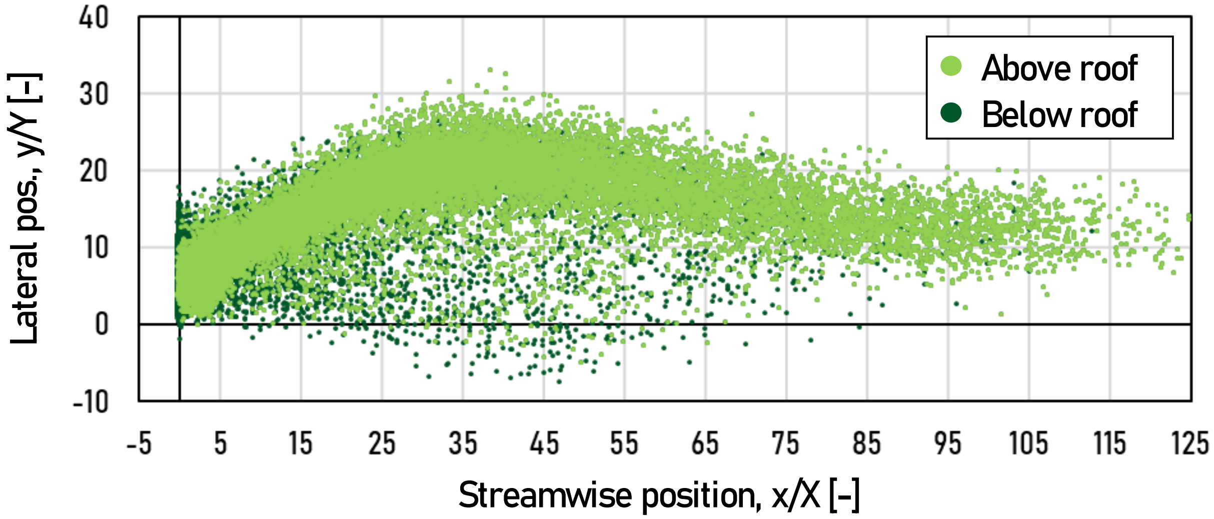
Dose field resulting from the continuous particle emission:



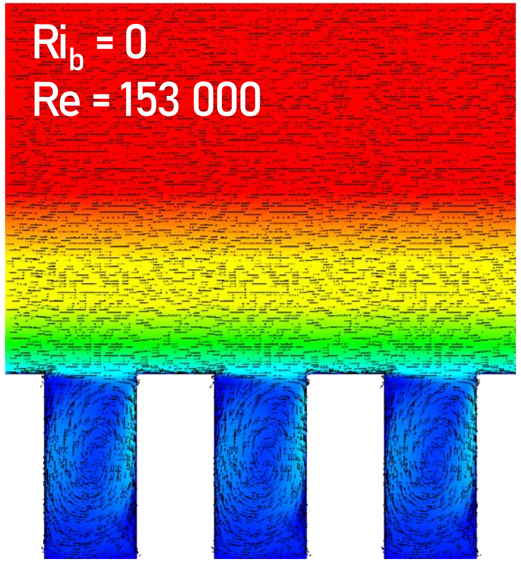
Model overview (present study)

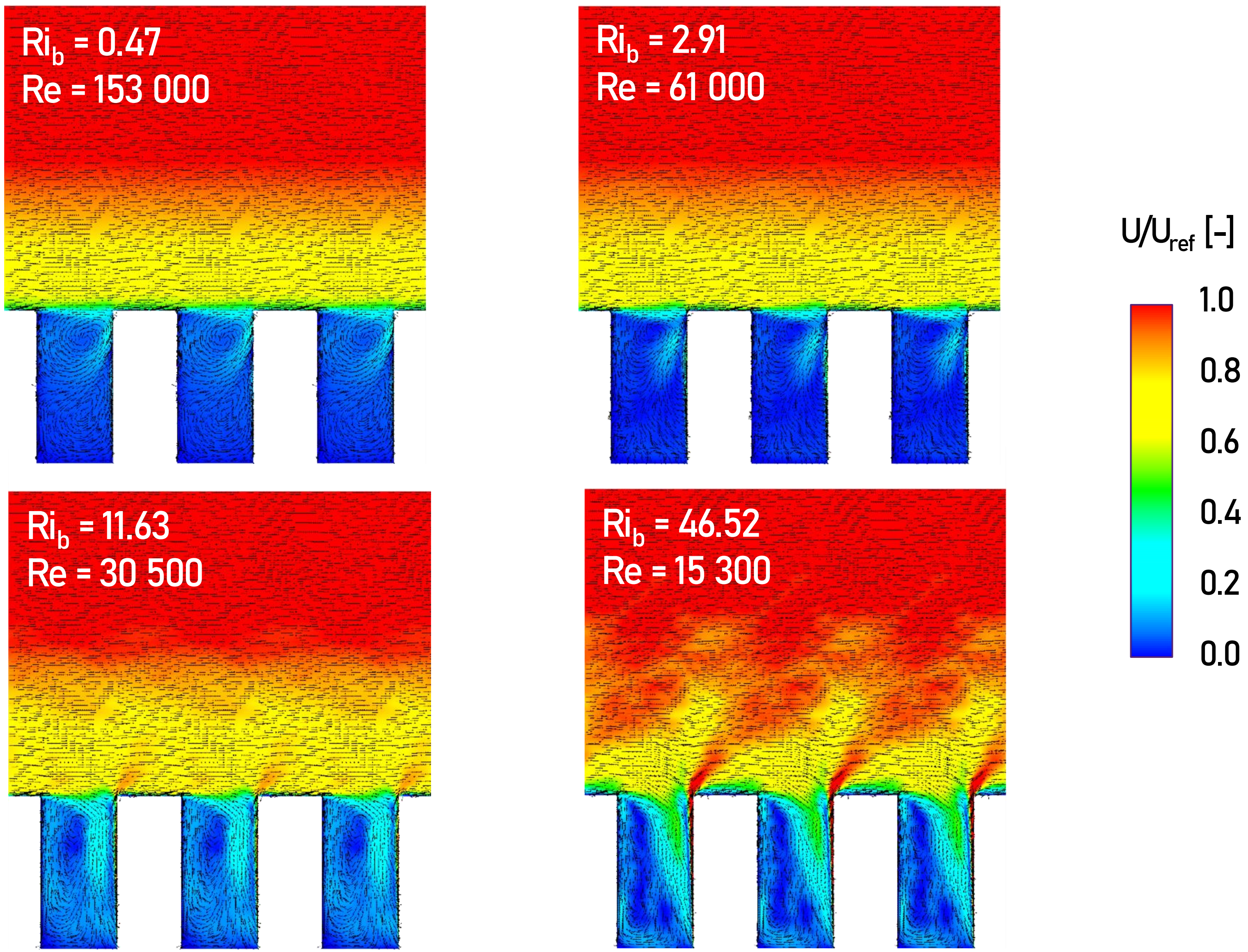


- Infinite series of parallel H/W = 2 street canyons
- Mesh resolution: W/32 + near-wall inflation
- TWF: measured time series (277 s) are imposed
- Particle emission: 50…150 s
- Solar radiation: roofs & downwind walls are heated (less favorable)



The effect of the bulk Richardson number



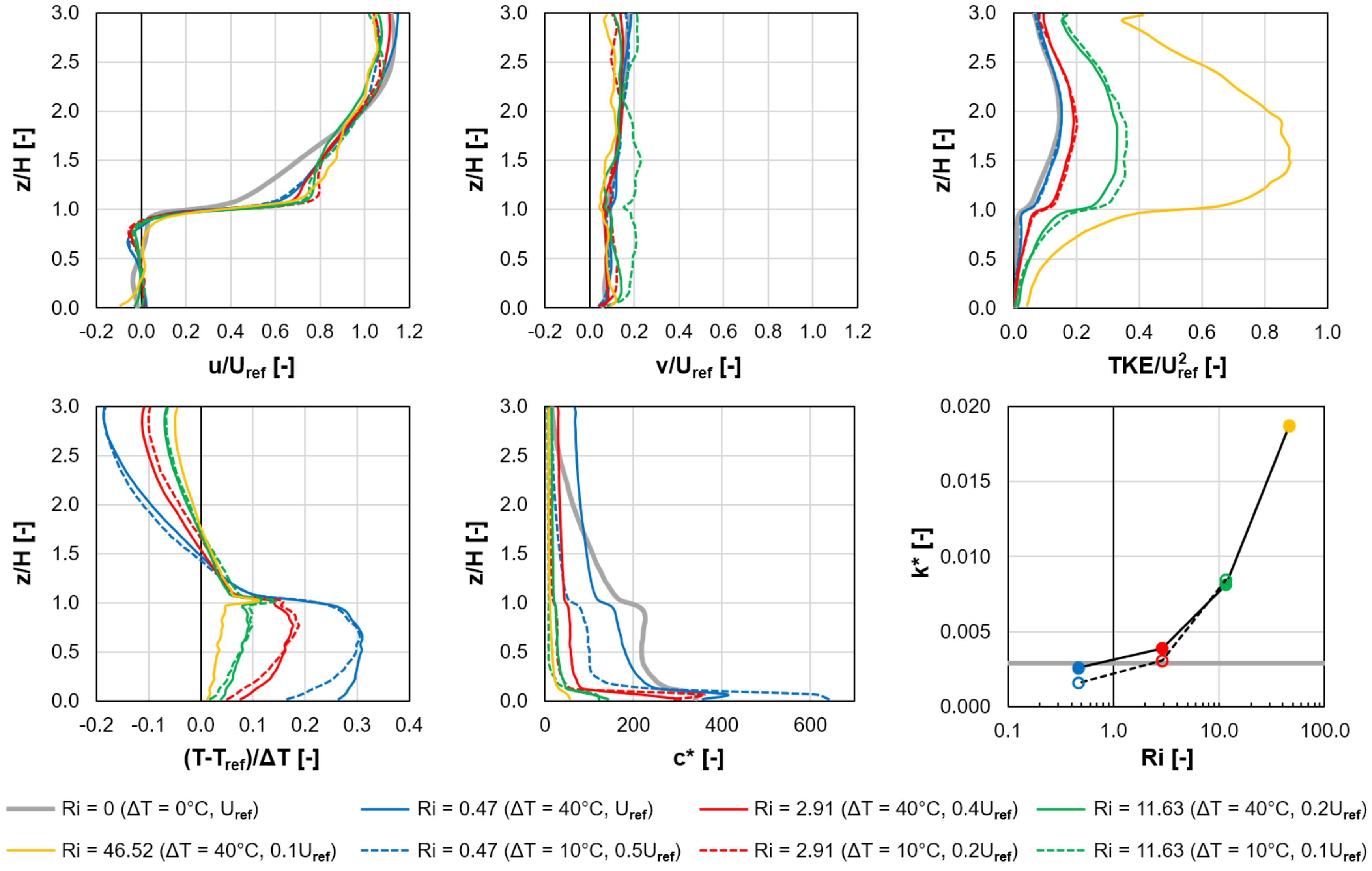


$U_{ref} = 0.187 \ldots 1.87$ [m/s]
$\Delta T = 0$ & 40 [°C]

$$(g > 0) \qquad Ri_b = \frac{gL\beta(T_{wall} - T_0)}{U_{ref}^2}$$

$$Re = \frac{LU_{ref}}{\nu}$$

Characteristic vertical profiles



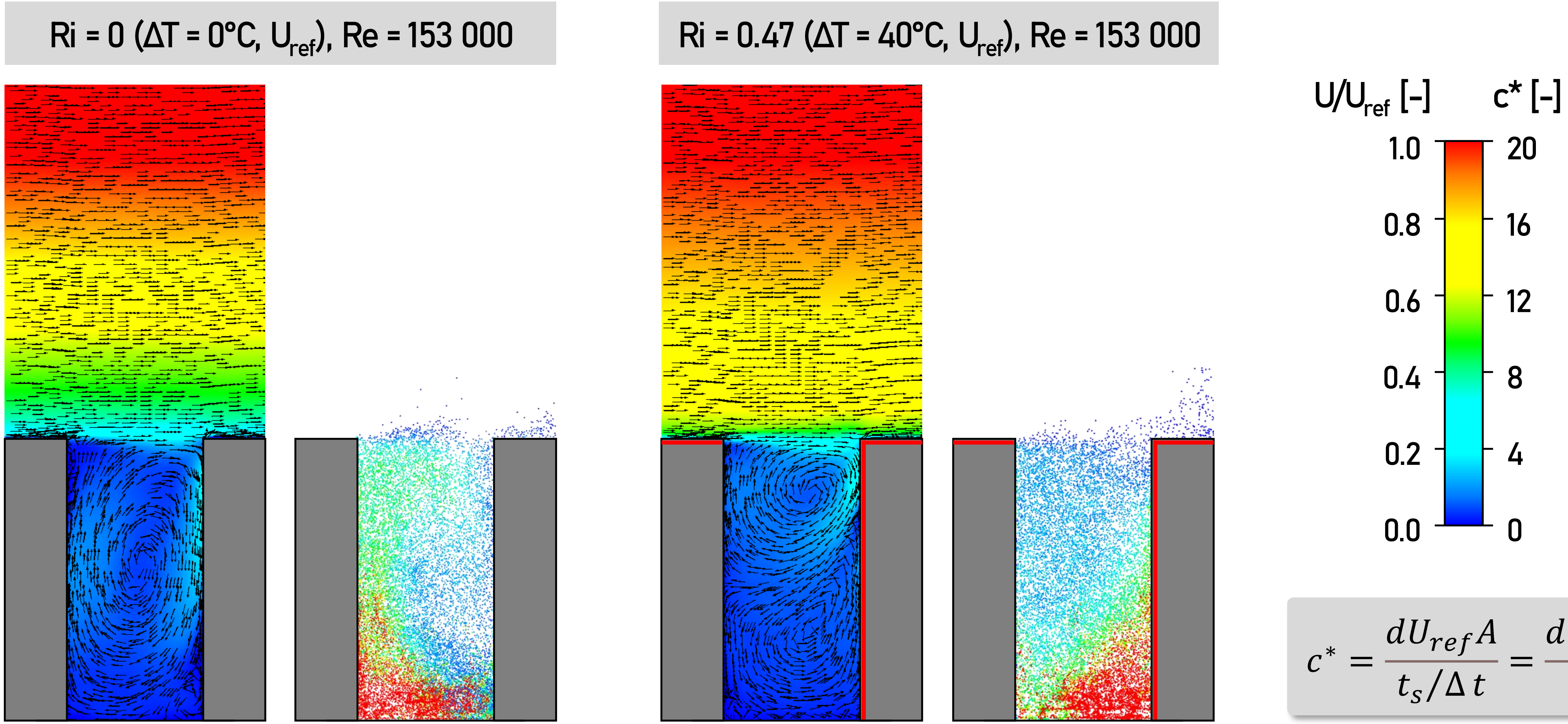
Normalized concentration:

$$c^* = \frac{dU_{ref}A}{t_s/\Delta t} = \frac{dU_{ref}A}{N_p}$$

Ventilation efficiency:

$$k^* = \frac{1}{c^*_{ng}}$$

The effect of heated walls



$$c^* = \frac{dU_{ref}A}{t_s/\Delta t} = \frac{dU_{ref}A}{N_p}$$

Xie, X., Huang, Z., Wang, J., & Xie, Z. (2005). The impact of solar radiation and street layout on pollutant dispersion in street canyon. Building and Environment, 40(2), 201-212.

Contributions & proposal for collaboration

- Periodic, measurement-driven LES model
  - ➢ Relatively small simulation domain
- The effects of natural wind can be taken into account
  - ➢ Transient Wind Forcing (TWF): imposing measured time series
  - ➢ The effects of flow structures exceeding the domain size can be modeled
- Long-distance dispersion can be calculated
  - ➢ Lagrangian particle tracking + counting the periodic jumps
  - ➢ Periodic flow field → aperiodic dispersion field
- Buoyancy and natural convection can also be modeled
- Validated for the isothermal cases (both velocity and dispersion)

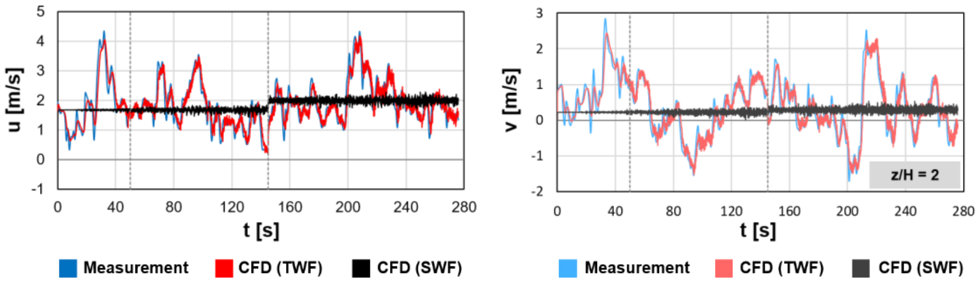



- For the validation of the thermal model, we need measurement data from new collaborators:
  - ➢ Field or wind tunnel experiments
  - ➢ Periodic or quasi-periodic geometry containing heated elements
  - ➢ High-frequency velocity time series for the TWF propulsion (full-scale: 1 Hz, covering 500...1000 flow-through times)
  - ➢ Time series from further gauging points for comparison of the velocity statistics and temperature results
  - ➢ The measurements may include concentration distributions as well

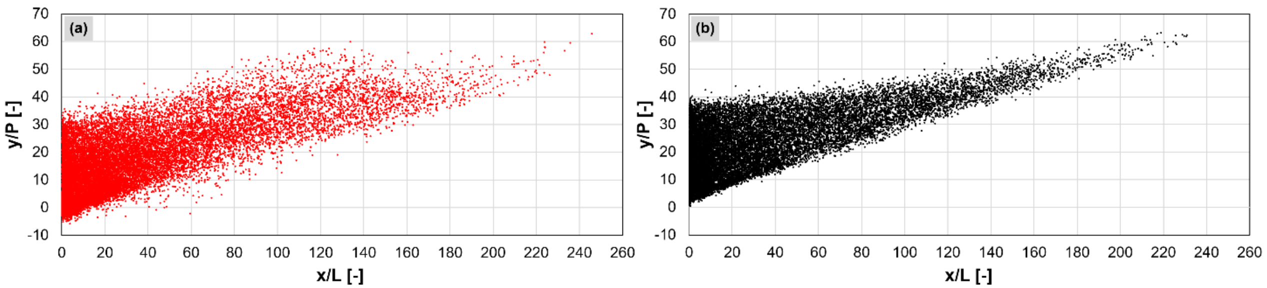
Supplementary slides

How much do the macroscopic fluctuations matter?

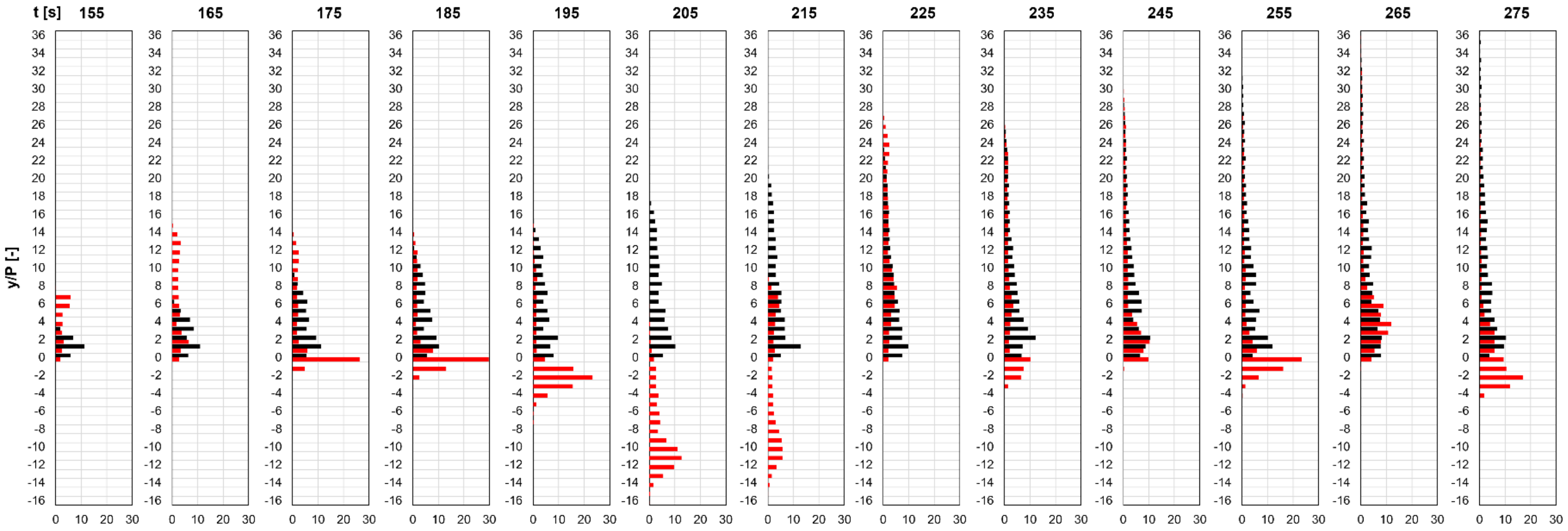
Velocity time series at the propulsion center



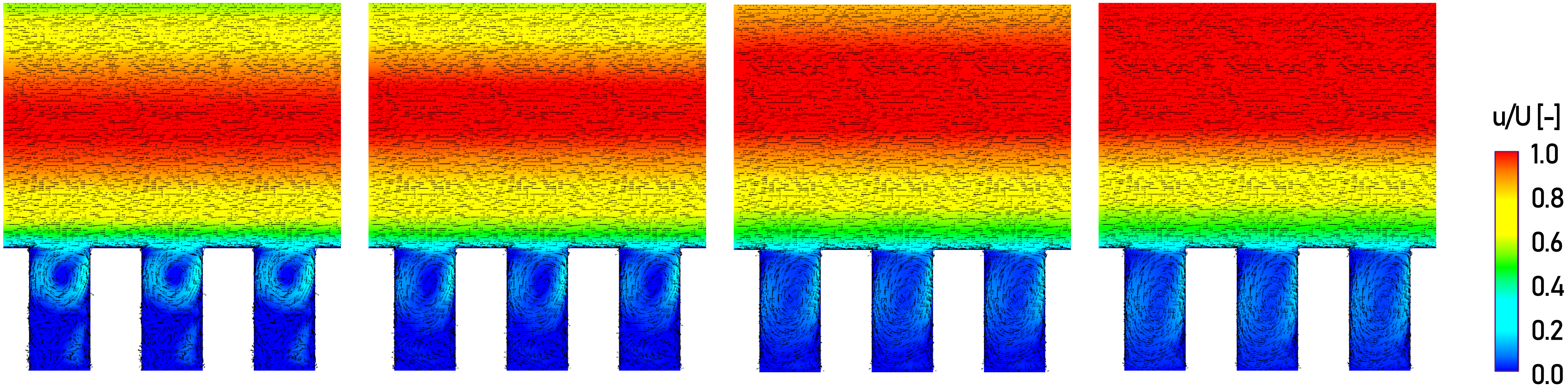
Plume shapes over the first 250 canyons (bird's eye view)



Lateral particle distributions in the first canyons over time



The effect of the Reynolds number



Re = 15 300
Ri = 0

Re = 30 500
Ri = 0

Re = 76 300
Ri = 0

Re = 153 000
Ri = 0

$U_{ref} = 0.187 \ldots 1.87 \; [\mathrm{m/s}]$
$\Delta T = 0 \; [°\mathrm{C}]$

$$Re = \frac{L U_{ref}}{\nu}$$

$$Ri = \frac{g L \beta (T_{wall} - T_0)}{U_{ref}^2} \quad (g > 0)$$

He, L., Hang, J., Wang, X., Lin, B., Li, X., & Lan, G. (2017). Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings. Science of the Total Environment, 584, 189-206.