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Session 5 – Topic ‘Urban scale and street canyon modelling: Meteorology and air quality’

LAGRANGIAN TIME SCALES OF THE TURBULENCE ABOVE TWO-DIMENSIONAL CANOPIES

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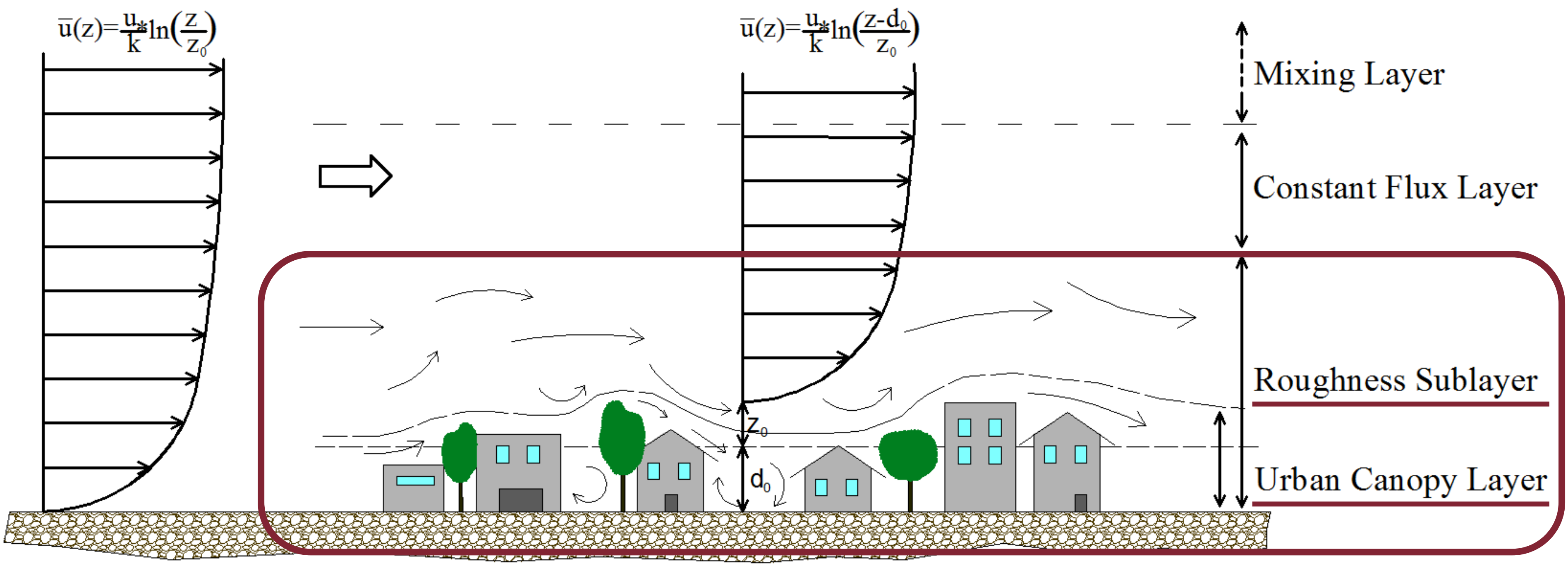
OUTLINE

1. ***Introduction***
2. ***Motivations and goals***
3. ***Theoretical framework***
4. ***Experimental setup and measurement technique***
5. ***Results***
6. ***Conclusions and further works***

1. INTRODUCTION – Physical phenomenon



$u_* = \sqrt{\bar{\tau}/\rho}$ ➡ friction velocity

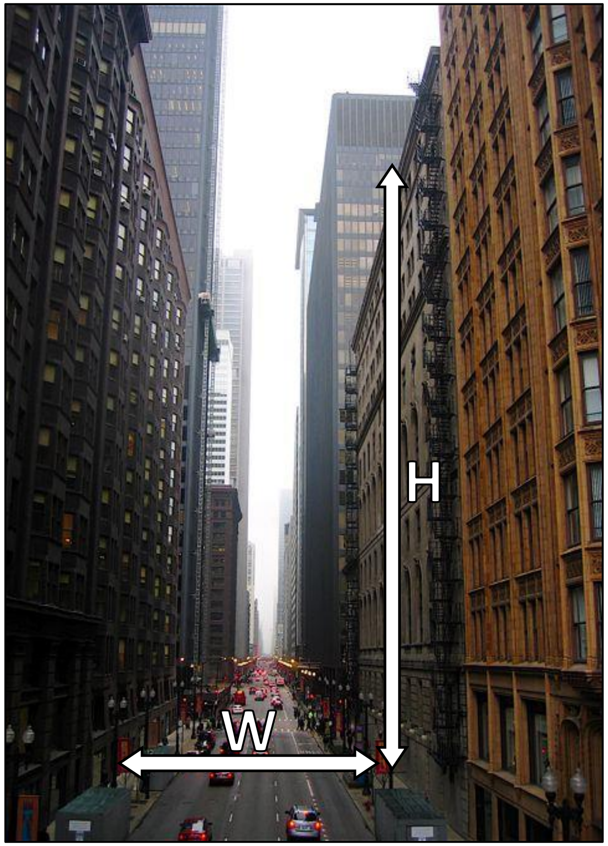
$k = 0.4$ ➡ Von Kàrmàn constant

z_0 ➡ aerodynamic roughness length

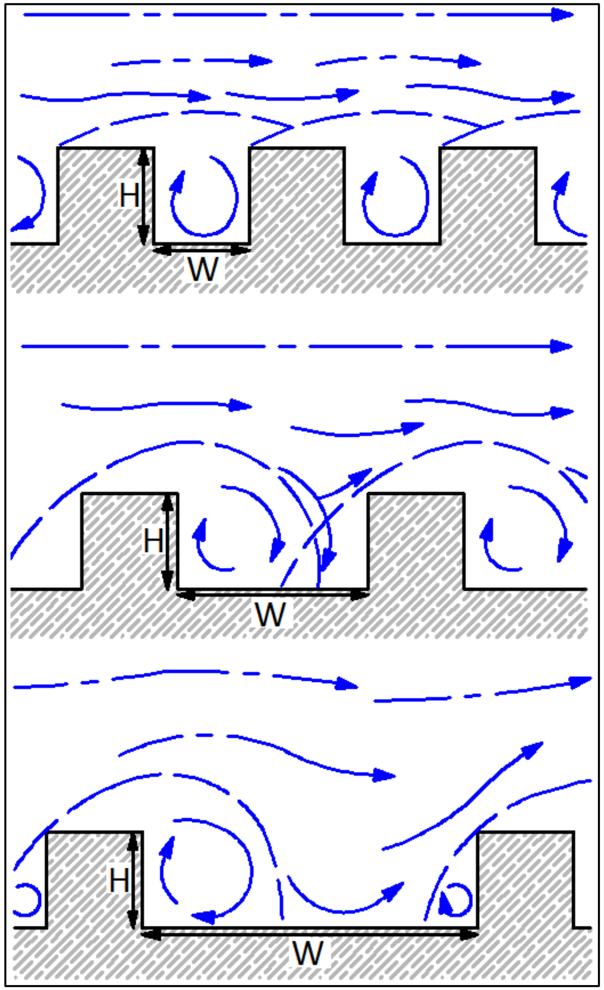
d_0 ➡ displacement height

1. INTRODUCTION – Physical phenomenon

Two-dimensional urban street canyon → Flow regimes classified by *Oke, 1987*



ASPECT RATIO: AR=W/H



SKIMMING FLOW
AR < 1.5

WAKE INTERFERENCE REGIME
1.5 ≤ AR ≤ 2.5

ISOLATED ROUGHNESS FLOW
AR > 2.5

2. MOTIVATIONS

Lagrangian time scales are fundamental for the development of *Lagrangian stochastic models (LSM)*, which are the most suitable tool for predicting pollutant concentration.

In LSM the particle's trajectory can be statistically calculated as *(Thomson 1987, JFM)*:

$$du_i = a_i dt + b_{ij} d\xi_j$$

a_i = particle acceleration along *i*-direction
b_{ij} = random forcing caused by the fluctuating pressure gradients and molecular diffusion

→ $b_{ij} = \sqrt{C_0 \varepsilon}\delta_{ij}$ → $C_0 = \dfrac{2\sigma^2}{T^L \varepsilon}$

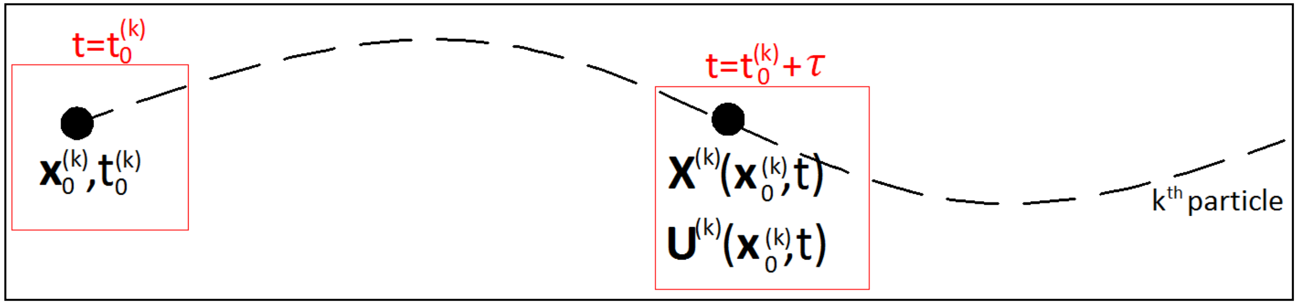
C_0 = Kolmogorov constant (2 ÷ 7)
ε = dissipation rate of the Turbulent Kinetic Energy
δ_{ij} = Kronecker delta

- Convective boundary layer → *Hanna 1981, JAM; Degrazia et al. 2000, AE*
- Vegetation canopies → *Molder et al. 2004, AFM; Poggi et al. 2008, AE; Haverd et al. 2009, BLM*
- Urban canopies → ???

2. GOALS

- ✓ ***Experimental investigation of 2D urban canopy flow***
- ✓ ***Experimental estimation of both streamwise and vertical components of the Lagrangian time scales over complex terrain***
- ✓ ***Analysis of the dependence of the Lagrangian time scales on the Aspect Ratio***
- ✓ ***Comparison between experimental data and parametric law (Raupach 1989, AFM)***
- ✓ ***Eulerian investigation of flow***
- ✓ ***Estimation of eddy diffusivity of momentum with different theoretical formulations***

3. THEORETICAL BACKGROUND – Lagrangian approach



Reference time: $t_0^{(k)}$
Reference position: $\boldsymbol{x}_0^{(k)}$
Time lag: $\tau = t - t_0^{(k)}$
Position at a generic time t: $\boldsymbol{X}^{(k)}$
Velocity at a generic time t: $\boldsymbol{U}^{(k)}$
Trajectories starting from $\boldsymbol{x}_0$: $M_{\boldsymbol{x}_0}$

<u>Lagrangian average velocity</u>: $\langle \boldsymbol{U} \rangle(\boldsymbol{x}_0,\tau) = \frac{1}{M_{\boldsymbol{x}_0}} \sum_{k|\boldsymbol{x}_0} \boldsymbol{U}^{(k)}(\boldsymbol{x}_0,\tau)$ (1)

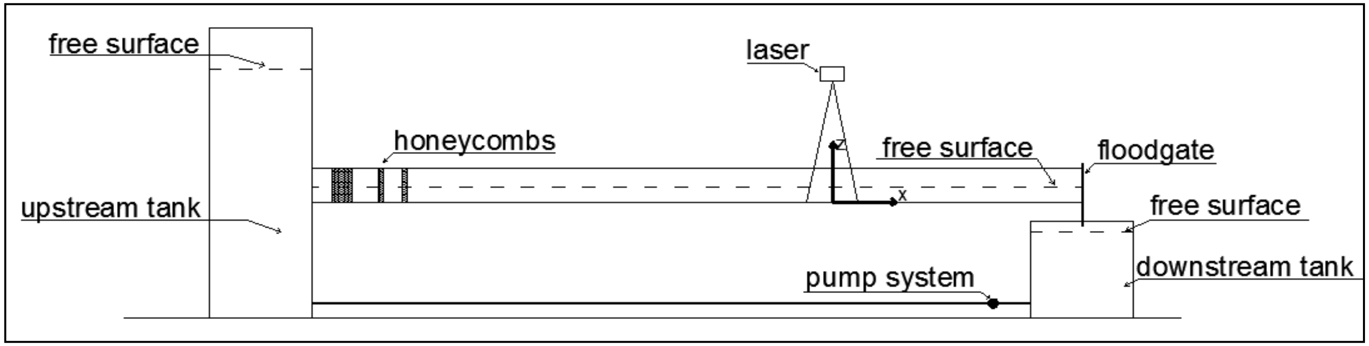
<u>Standard deviation of the *j*-th component of the velocity</u>: $\sigma_j^L(\boldsymbol{x}_0,\tau) = \sqrt{\frac{1}{M_{\boldsymbol{x}_0}} \sum_{k|\boldsymbol{x}_0} \left[U_j^{(k)}(\boldsymbol{x}_0,\tau) - \langle U_j \rangle(\boldsymbol{x}_0,\tau)\right]^2}$ (2)

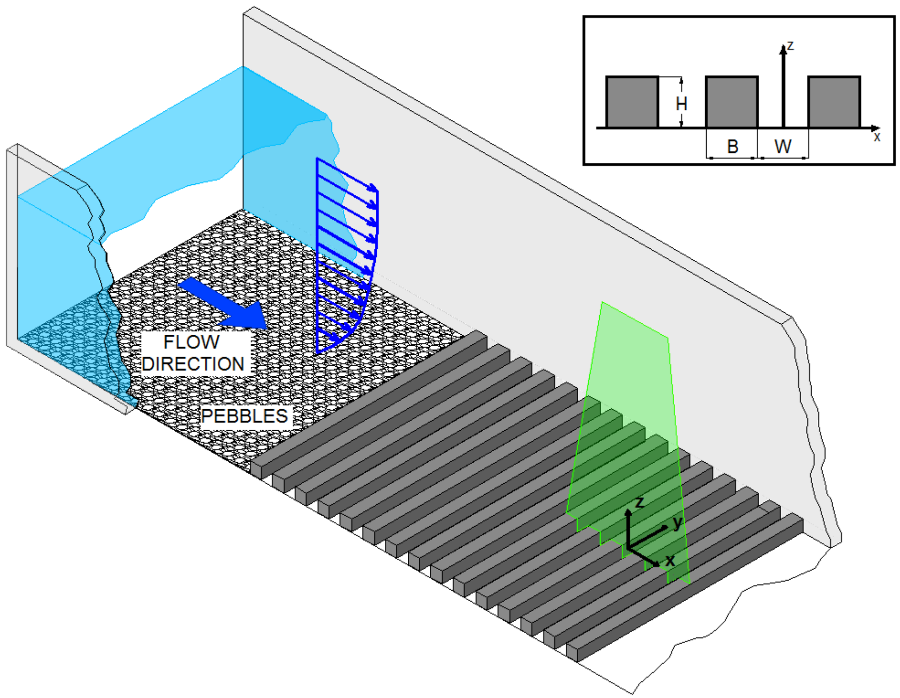
<u>Auto-correlation coefficient</u>: $\rho_j^L(\boldsymbol{x}_0,\tau) = \frac{1}{M_{\boldsymbol{x}_0}} \frac{\sum_{k|\boldsymbol{x}_0}\left\{\left[U_j^{(k)}(\boldsymbol{x}_0,\tau) - \langle U_j \rangle(\boldsymbol{x}_0,\tau)\right]\left[U_j^{(k)}(\boldsymbol{x}_0,0) - \langle U_j \rangle(\boldsymbol{x}_0,0)\right]\right\}}{\sigma_j^L(\boldsymbol{x}_0,\tau)\sigma_j^L(\boldsymbol{x}_0,0)}$ (3)

<u>Lagrangian time scale of the j-th velocity component</u>: $T_j^L(\boldsymbol{x}_0) = \int_0^\infty \rho_j^L(\boldsymbol{x}_0,\tau)d\tau$ (4)

The Lagrangian time scale can be rigorously defined only for homogeneous, isotropic turbulence.
For inhomogeneous turbulence, T_j^L are not the Lagrangian time scales but local decorrelation time scales, which could be interpreted as a measure of the persistence of motion along the *j*-th direction.

4. EXPERIMENTAL SETUP – Laboratory facility





WATER-CHANNEL DIMENSIONS

- height: 0.35 m
- width: 0.25 m
- length: 7.40 m

GEOMETRICAL CONFIGURATIONS

B = H = 20 mm

W = 20 mm ➡ AR = 1 (skimming flow)

W = 40 mm ➡ AR = 2 (wake interference regime)

FLOW CHARACTERISTICS

- water depth: 0.16 m
- freestream velocity (U): 0.33 m s^{-1}
- friction velocity ($u_{*\,ref}$): from 0.019 to 0.027 m s^{-1}
- Reynolds number ($Re_{\tau}=u_{*\,ref}H/\nu$) = from 390 to 470

4. EXPERIMENTAL SETUP – Measurement technique

EULERIAN STATISTICS

High Speed-CMOS-Camera
- resolution: 1280 × 1024 pixels
- frame rate: 250 Hz
- sample: 40 s (10000 frames)

LD PUMPED ALL-SOLID-STATE GREEN LASER
- wavelength: 532 nm
- thickness: 2 mm
- power: 5 W

Framed area
- 0.06 m long (x-axis) 0.06 m high (z-axis)

RESULTS

- velocity field over a 120x120 regular array
- spatial resolution: 0.5 mm
- temporal resolution: 1/250 s

LAGRANGIAN STATISTICS

High Speed-CMOS-Camera
- resolution: 1280 × 1024 pixels
- frame rate: 500 Hz
- sample: 120 s (60000 frames)

COBRA SLIM - HALOGEN WHITE LAMP
- thickness: 20 mm
- power: 1000 W

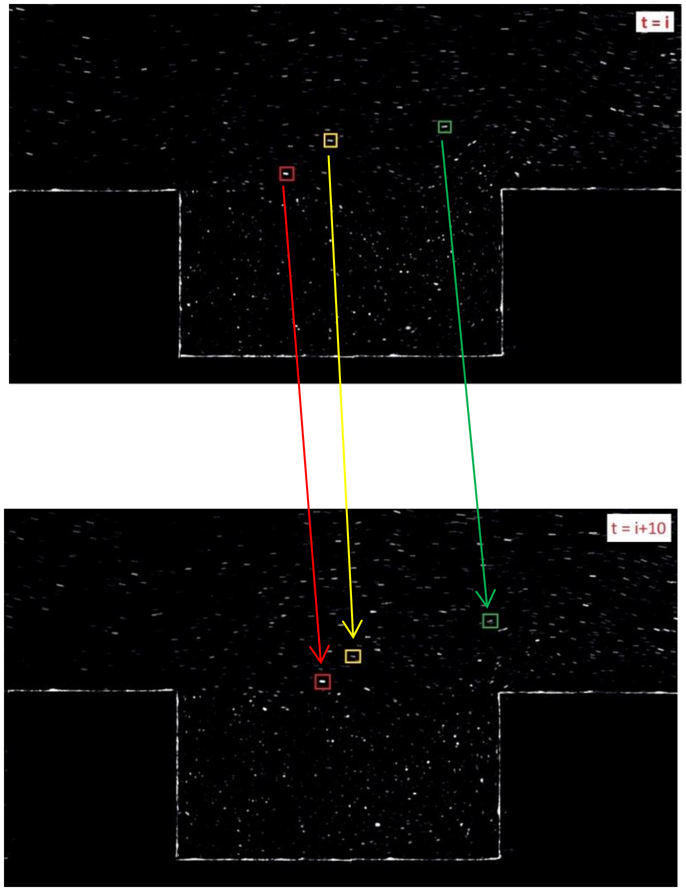
Framed area
- 0.2 m long (x-axis) 0.06 m high (z-axis)

RESULTS

- Lagrangian time scale for layers 1 mm tick above the canopy
- trajectories n.: ≈ 200000
- temporal resolution: 1/500 s

4. EXPERIMENTAL SETUP – Measurement technique

<u>FEATURE TRACKING (FT)</u> ➔ Image analysis technique that allows the identification of features basing on brightness gradients in following frames.



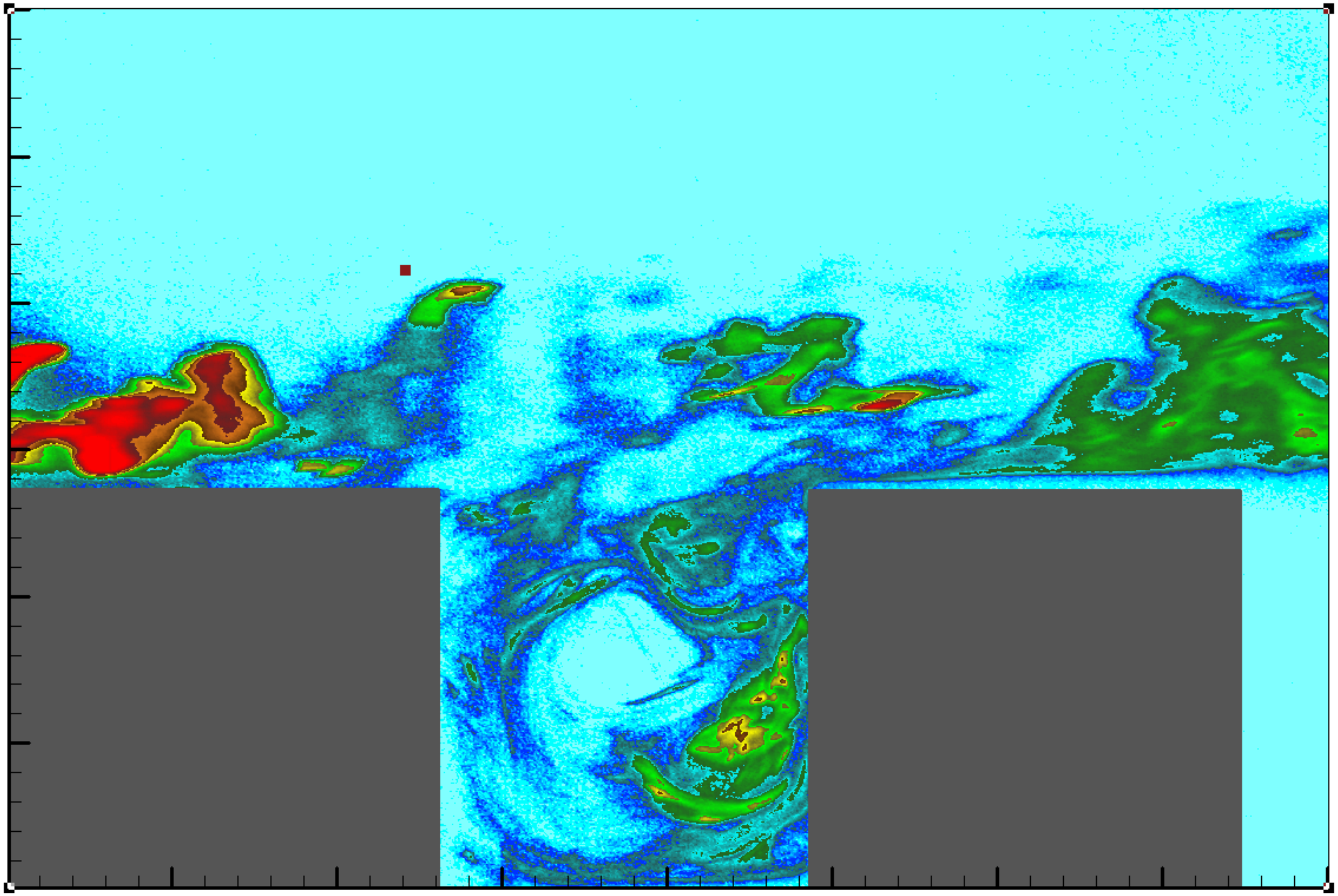
1. Identification and subtraction of the background from frames
2. Feature identification
3. Choice of the *best feature* to track
4. Comparison of brightness at each pixel in consecutive images
5. Reconstruction of velocity fields with scattered data on the x-z plane

<u>Eulerian</u> description of the velocity field over a regular 120x120 array

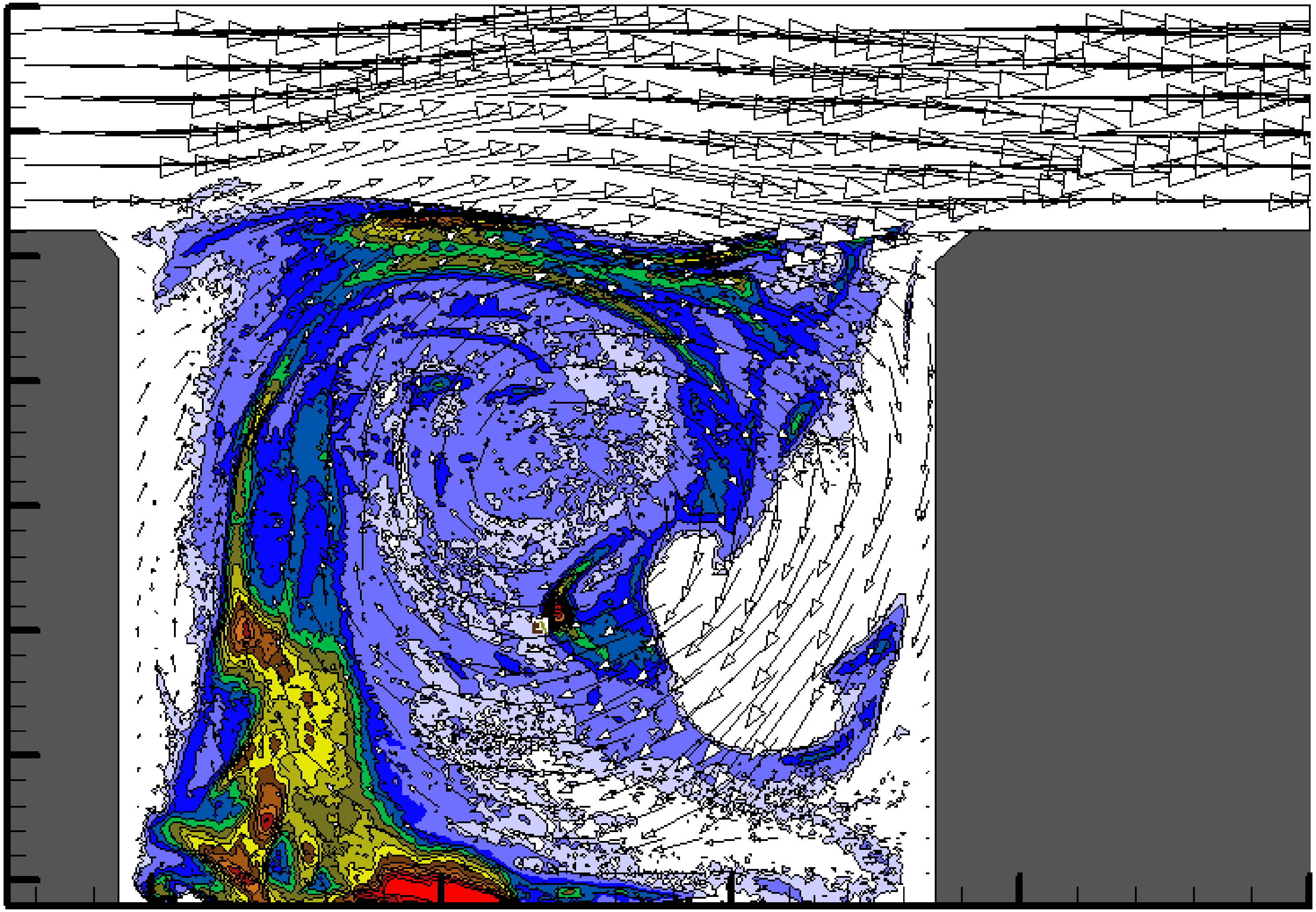
Tracking of the particle trajectories for the evaluation of the *<u>Lagrangian</u>* statistics.

Identification of trajectories long enough to calculate integral time scales

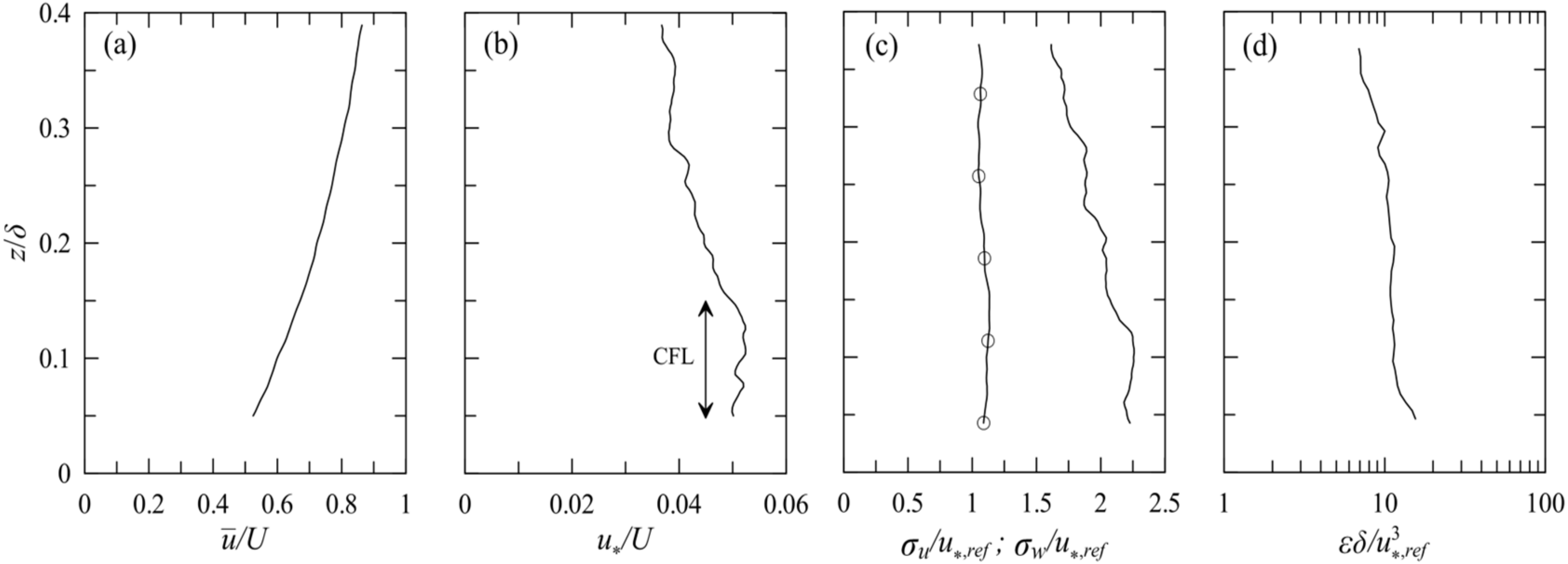
4. EXPERIMENTAL SETUP – Measurement technique



4. EXPERIMENTAL SETUP – Measurement technique



5. RESULTS – Inflow



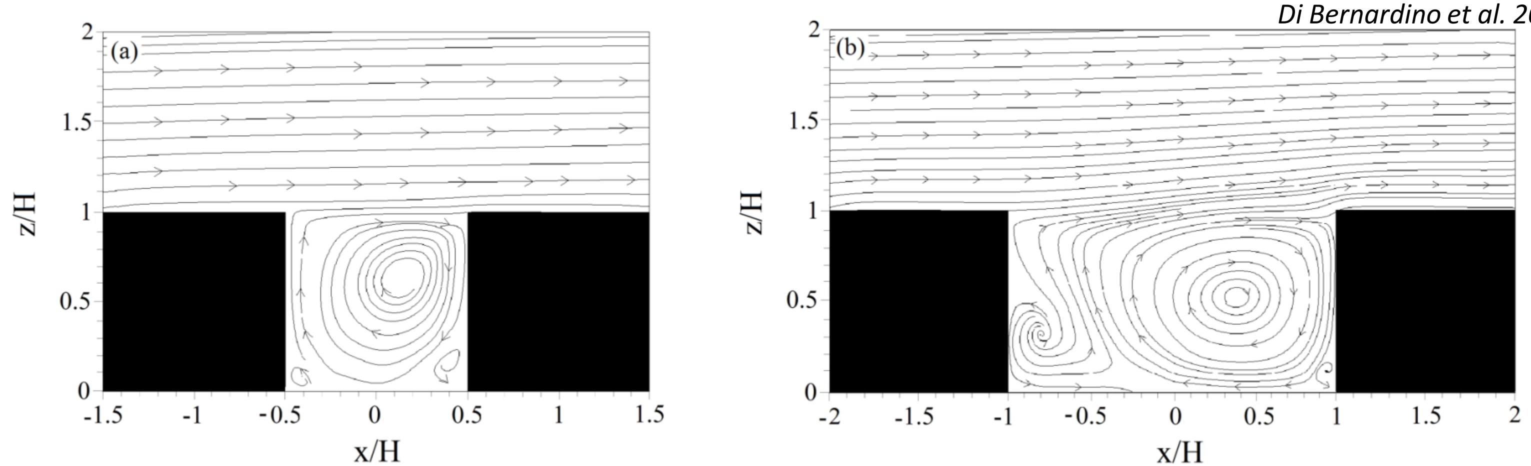
- average pebbles diameter: 5 mm
- turbulent boundary-layer depth δ: 0.14 m
- reference friction velocity $u_{*,ref}$: 0.017 m s^{-1}

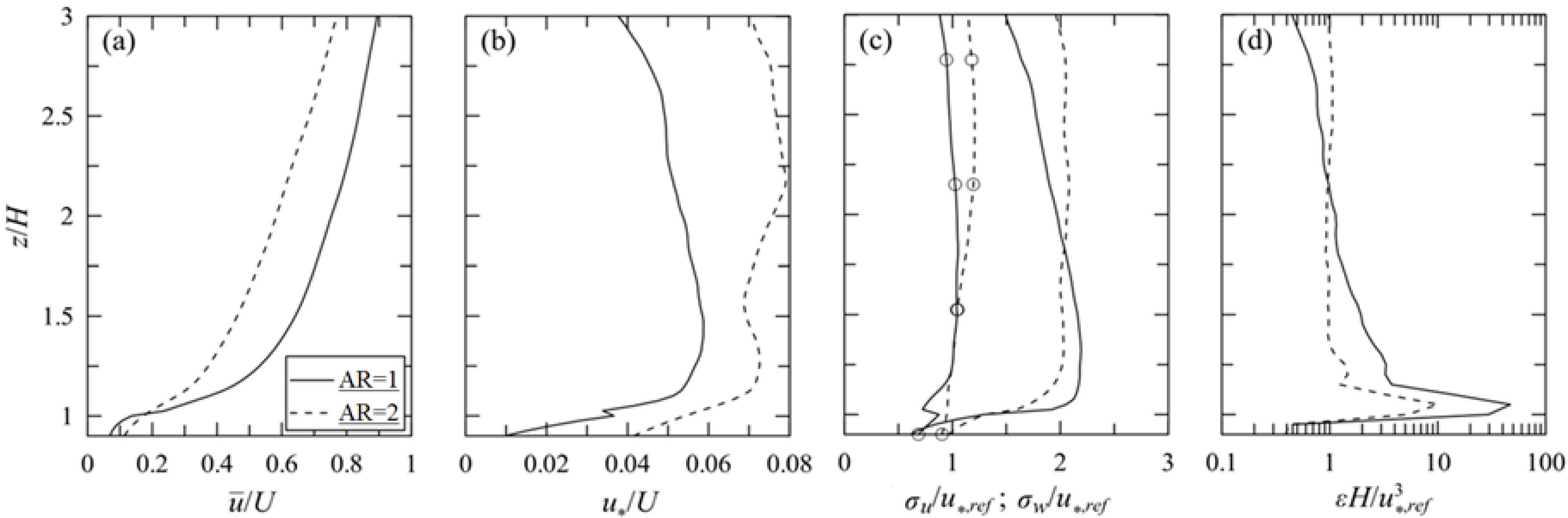
Streamwise mean velocity: $\bar{u} = \frac{u_{*,ref}}{k} \ln \frac{(z-d_0)}{z_0}$ (5) → fitting → $d_0 = 0$, $z_0 = 0.0003$ m

Dissipation rate of the Turbulent Kinetic Energy (*Hinze 1975*) $\varepsilon = \frac{15}{4}\nu\left[\overline{\left(\frac{\partial u'}{\partial z}\right)^2 + \left(\frac{\partial w'}{\partial z}\right)^2}\right]$ (6)

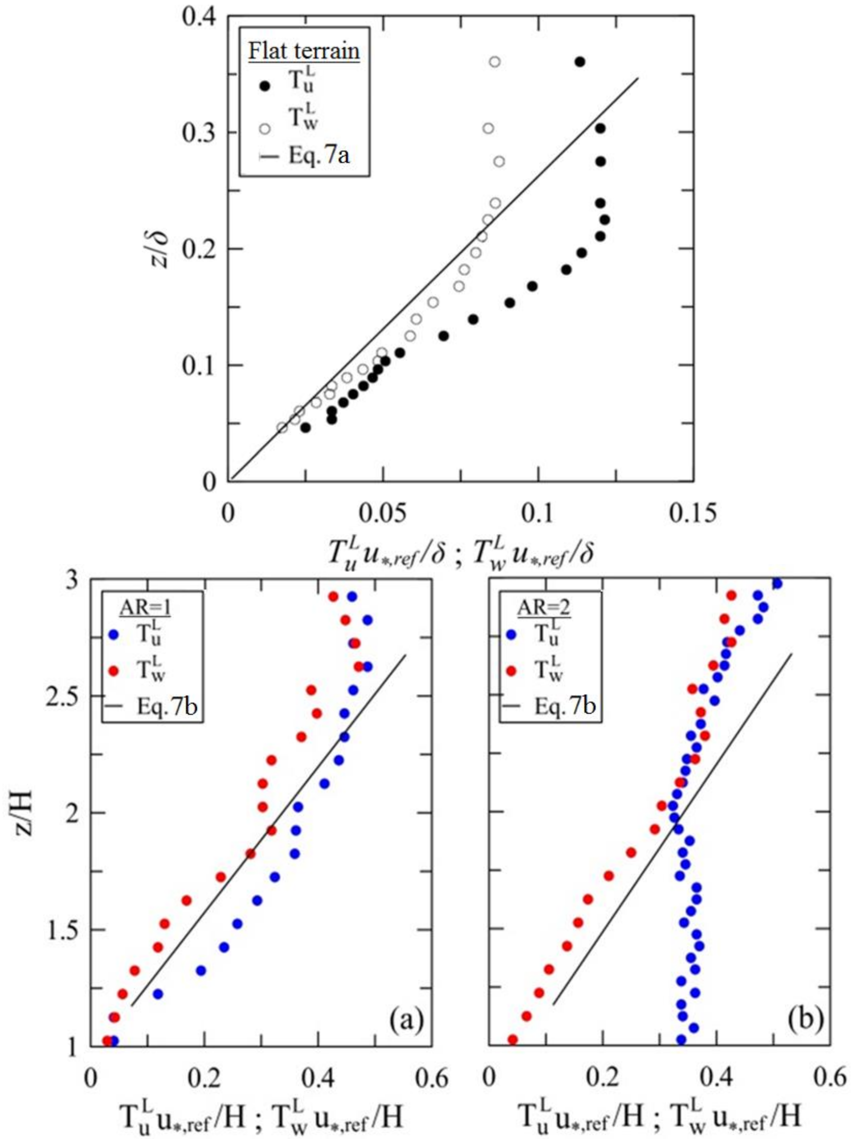
5. RESULTS – Eulerian statistics

Di Bernardino et al. 2017, BLM





5. RESULTS – Lagrangian time scales



- In case of flat terrain, T_u^L and T_w^L greatly increase with height
- T_w^L for $z/\delta \lesssim 0.2$ (i.e. into the CFL) grows in agreement with Eq. (7a) by *Raupach 1989, AFM*

$$\frac{T_w^L u_{*ref}}{\delta} = \frac{k}{([\sigma_w/u_*]_{ref})^2}\frac{z}{\delta} \quad (7a)$$

- For $z/\delta \gtrsim 0.2$ T_u^L and T_w^L are nearly constant in the case of flat terrain
- For AR=1, T_u^L and T_w^L grow almost linearly with height for the whole boundary layer
- T_u^L and T_w^L for AR=1 T_w^L for AR=2 grow in agreement with Eq. (7b)

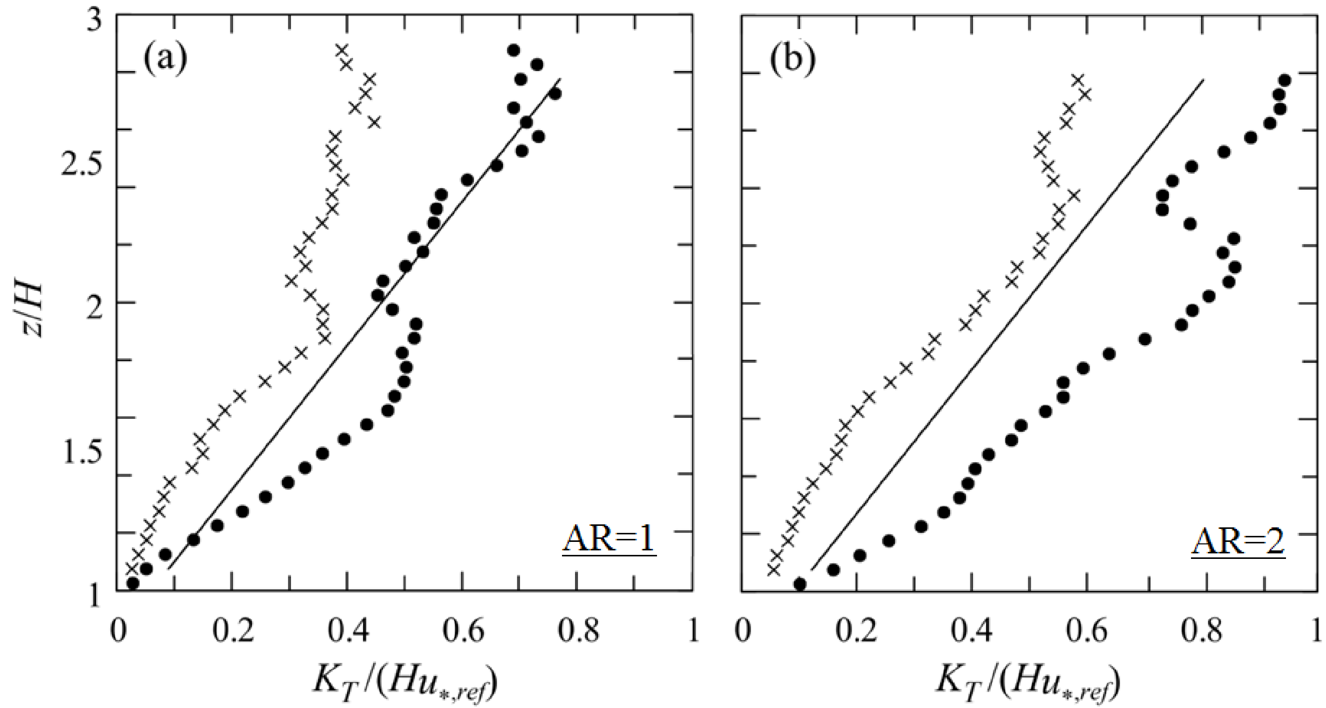
$$\frac{T_w^L u_{*ref}}{H} = \frac{k}{([\sigma_w/u_*]_{ref})^2}\frac{z-d_0}{H} \quad (7b)$$

where d_0=0.9H and d_0=0.77H for AR=1 and 2, respectively (*Kastner-Klein and Rotach 2004, BLM)*

- For AR=2, T_u^L is constant in the whole RSL as well as for a considerable portion of CFL. For $z > 2H$, it grows roughly linearly with height
- For AR=2, $T_u^L \approx T_w^L$ for $z > 2H$
- T_w^L do not change appreciably with AR

Di Bernardino et al. 2017, BLM

5. RESULTS – Turbulent diffusivity



- • $K_T = -\overline{u'w'}\,d\bar{u}/dz$ (8)

  relies on the first-order closure for the momentum flux

- × $K_T = \sigma_w^2 T_w^L$ (9)

  eddy diffusivity based on Taylor's theory

- – $K_T = k u_{*,ref}(z - d_0)$ (10)

  eddy diffusivity based on Prandtl's mixing-length theory

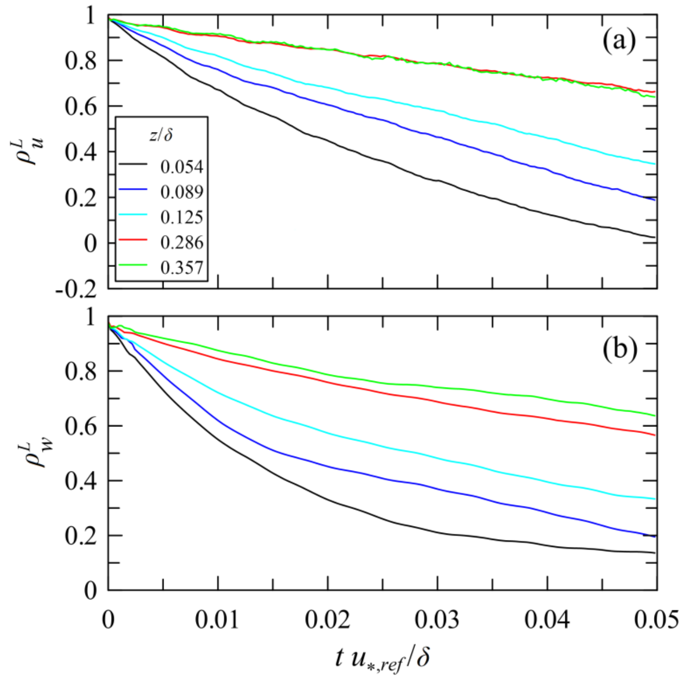
- Satisfactory agreement for AR=1
- For AR=2 disparities of a factor of 2 between Eqs. 8 and 9 occur for the whole domain
- Eq. 8 and Eq. 9 grow roughly linearly with height according to Prandtl's law, even though with different slopes.

6. CONCLUSIONS AND FURTHER WORK

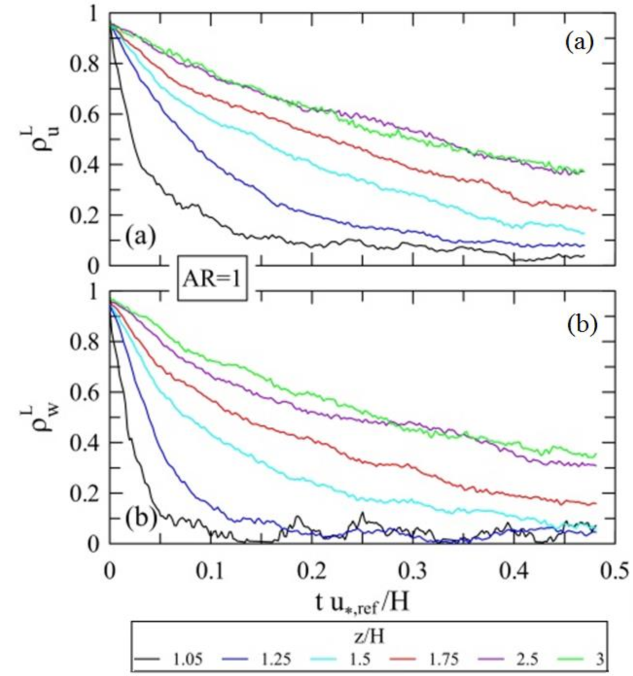
- ✓ **Experimental determination of streamwise and vertical components of the Lagrangian time scales (not previously reported in the literature)**
- ✓ **For AR=1, T_u^L and T_w^L grow linearly with height. For AR=2, T_u^L is almost constant for z<2H and T_w^L grows linearly with height**
- ✓ **Dependence of the streamwise component of the time scale T_u^L on AR, independence of the vertical component of the time scale T_w^L on AR**
- ✓ **Comparison of streamwise and vertical components of the Lagrangian time scales with theoretical prediction: T_u^L and T_w^L obey Raupach's law (except T_w^L when AR=2)**

- ❖ **Analysis of the Lagrangian time scales within the cavities**
- ❖ **Investigation for other Aspect Ratios of the canopy**
- ❖ **Comparison with other theoretical laws**
- ❖ **Investigation above and within three-dimensional geometries, varying the building height and the planar area fraction**

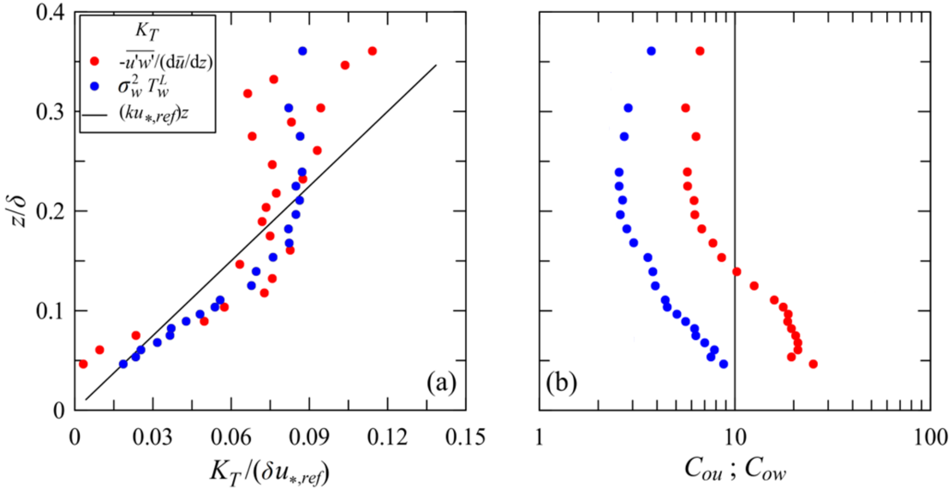
Thank you for your attention!



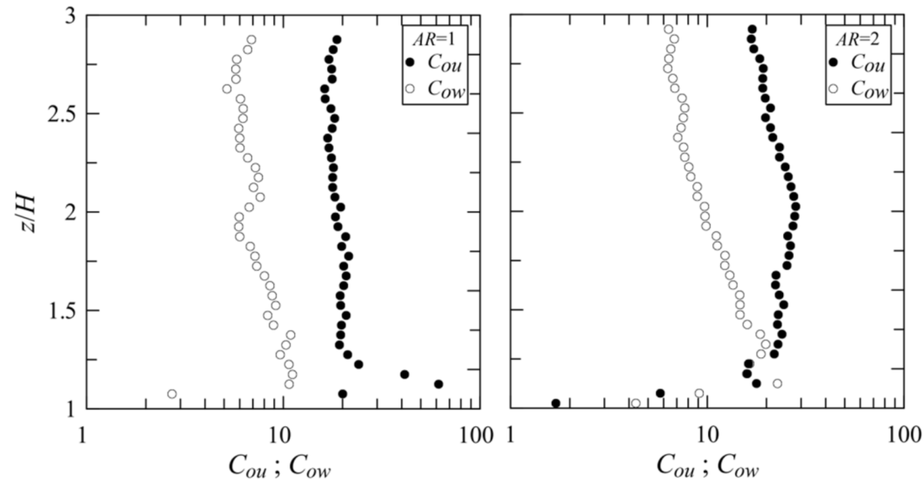
FLAT TERRAIN: Lagrangian autocorrelation functions calculated at various heights for the (a) streamwise and (b) vertical velocity component.



CANOPIES: Lagrangian autocorrelation functions calculated at various heights for the (a) streamwise and (b) vertical velocity component for AR=1.



FLAT TERRAIN: (a) Vertical profiles of the non-dimensional turbulent diffusivity and (b) of the Kolmogorov constants (Red and blue refer to $C0u$ and $C0w$, respectively).



CANOPIES: Vertical profiles of the Kolmogorov constants .