Urban wind flow CFD simulations and validation against wind tunnel experiments in two facilities

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César Sánchez Aguado

csanagu@upv.edu.es

Clean Mobility & Thermofluids

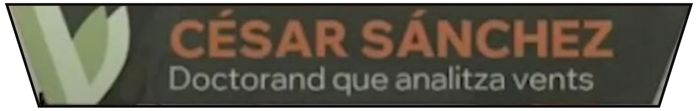
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ETSI Aeroespacial y Diseño Industrial

MuMFC MÁSTER UNIVERSITARIO EN MECÁNICA DE FLUIDOS COMPUTACIONAL

ATTENDANCE

- My profile



  - Aerospace engineering (2023)
  - MUMFC (2025)
  - **PhD program in CMT:** Numerical and experimental characterization of urban wind flow for air mobility
    - Participation in MODERA: TED2021-131087A-I00
    - C. Sánchez-Aguado, P. Varela, P. Quintero, R. Navarro, S. Franchini, R. Manzanares-Bercial, M. Ogueta-Gutiérrez, I. Quintanilla, A. Gallego-Salguero, "Validation of multi-fidelity urban flow numerical model for innovative air mobility against wind tunnel experiments in two facilities" [preprint], submitted to Journal of Wind Engineering and Industrial Aerodynamics in October 2025. DOI: https://doi.org/10.5281/zenodo.17454535

0. Introduction
1. Experimental studies
2. Numerical simulations
3. Future work

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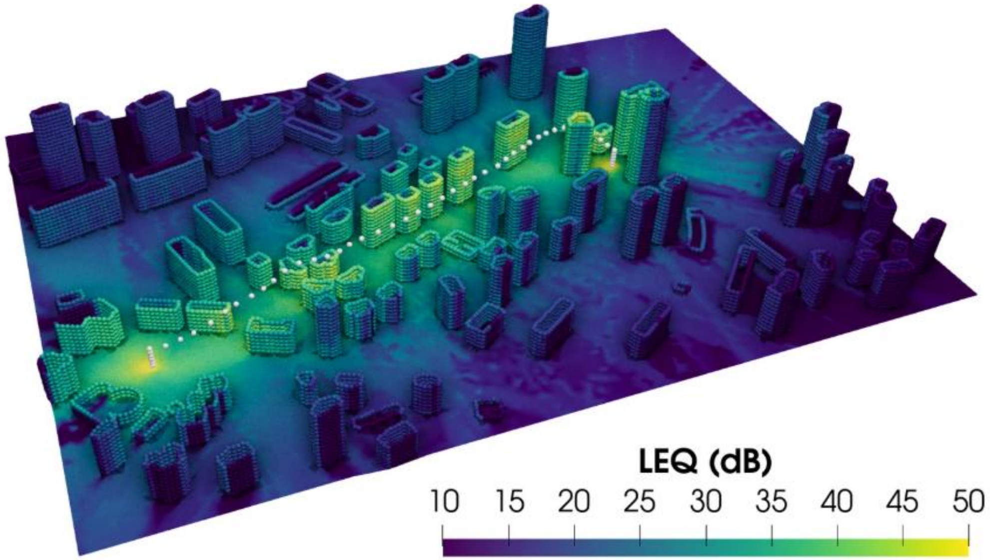
0. Introduction

- **Motivation**
- **Case study**

1. Experimental studies
2. Numerical simulations
3. Future work

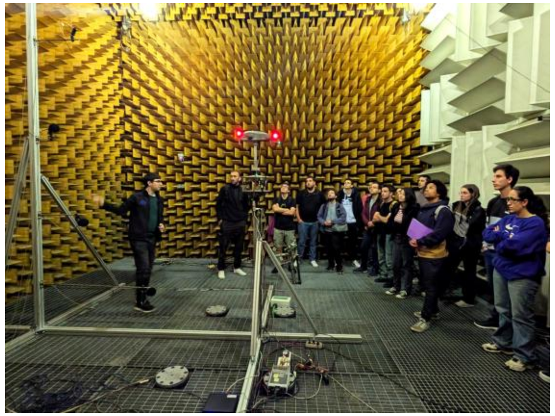
0. Introduction

- Motivation
  - Urban Air Mobility (UAM)
  - MODERA: noise reduction of UAVs in urban environments
  - Urban flows driven by wake interactions
  - Need to bound experimental and numerical uncertainty
  - Need to analyze **complex scenarios** for **UAV trajectory optimization**

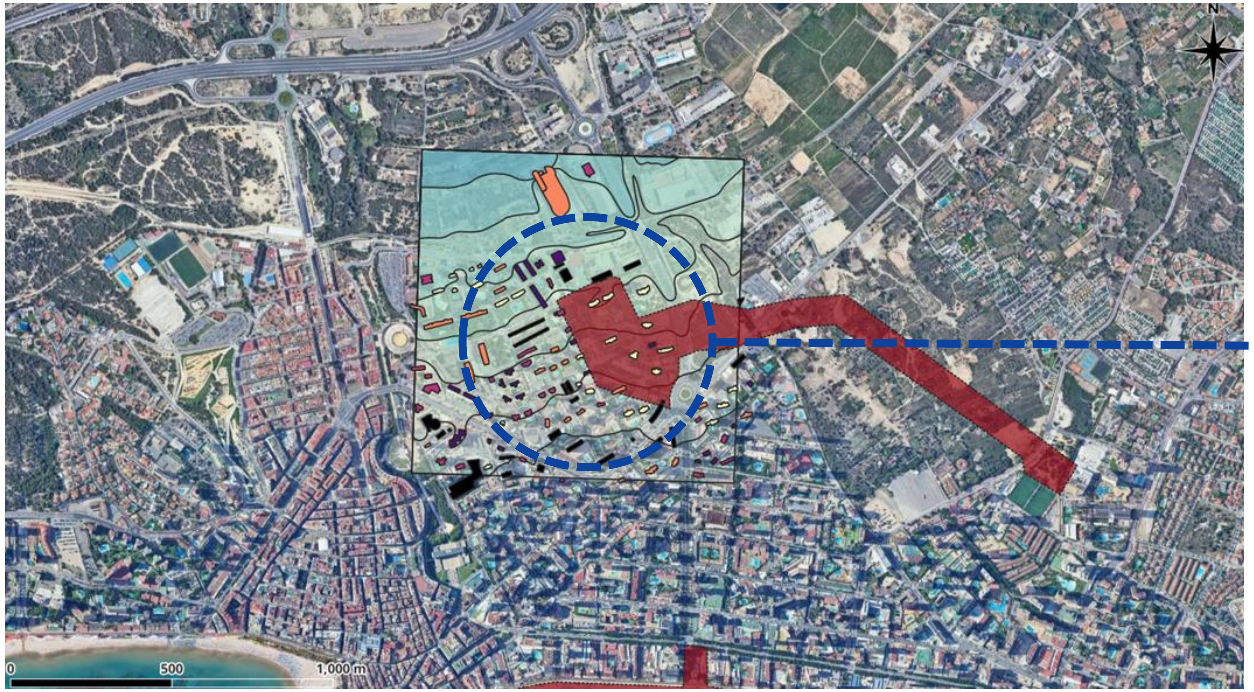


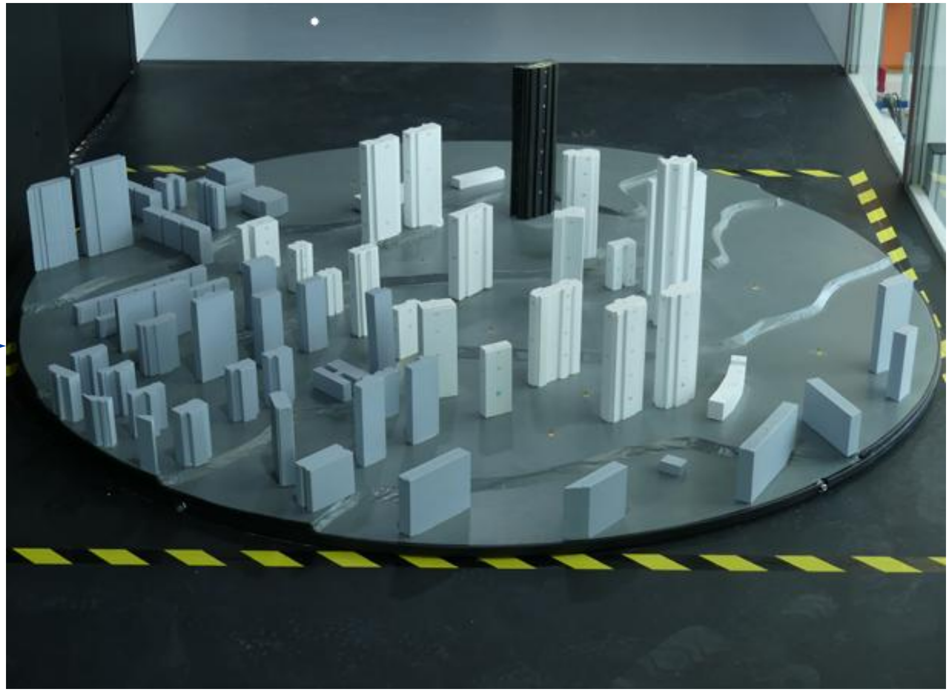
0. Introduction

- About MODERA (*MOdelos Digitales para la Evaluación y Reducción de la contaminación Acústica generada por UAS en entornos urbanos*)
  - Project overview
  - Access to publications
  - Data available at open-access repository
  - Latest news

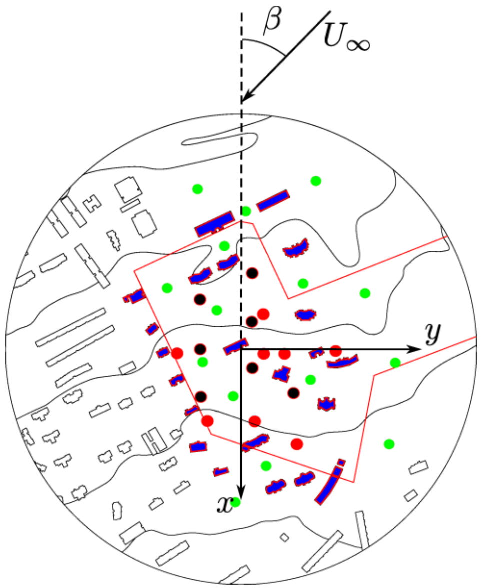



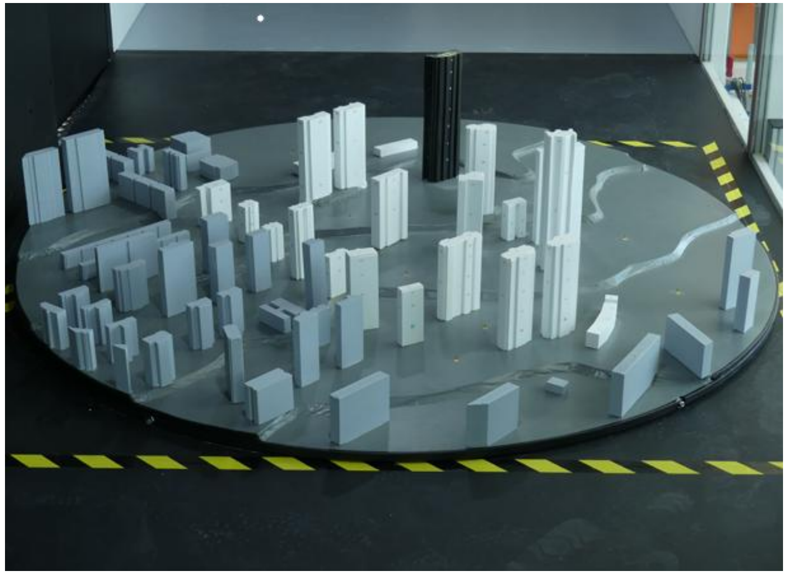

- Case study
  - Benidorm Urban Lab → future UAV flight field tests
  - Reproducible LiDAR/cadastral-derived mockup
  - Scale 1:375

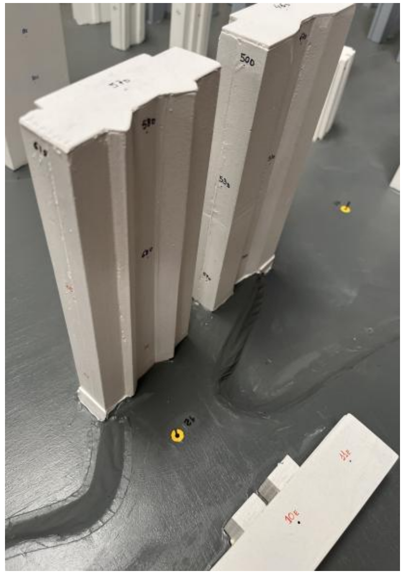


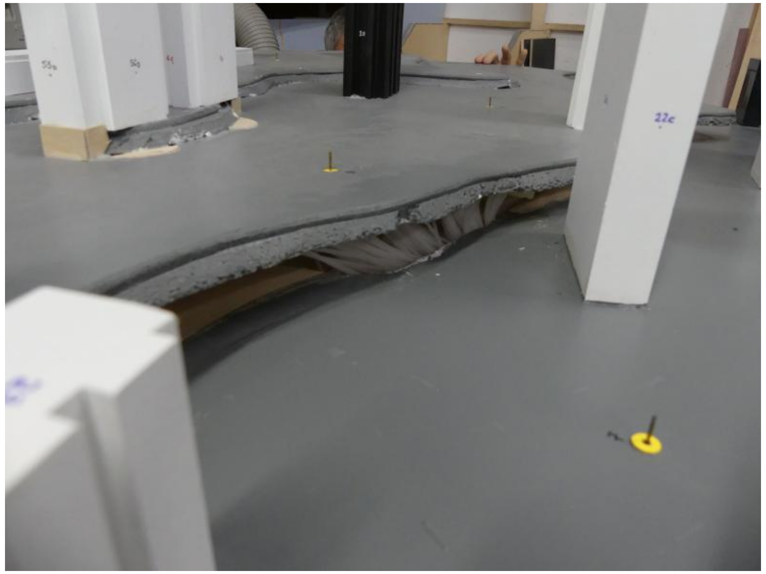


- Instrumental measurements:
    - Hot-wire vertical probes (for $\boldsymbol{\beta}$=0º and $\boldsymbol{\beta}$=180º)
    - Pressure probes at **instrumented buildings**
    - Irwin probes
    - Used for CFD validation

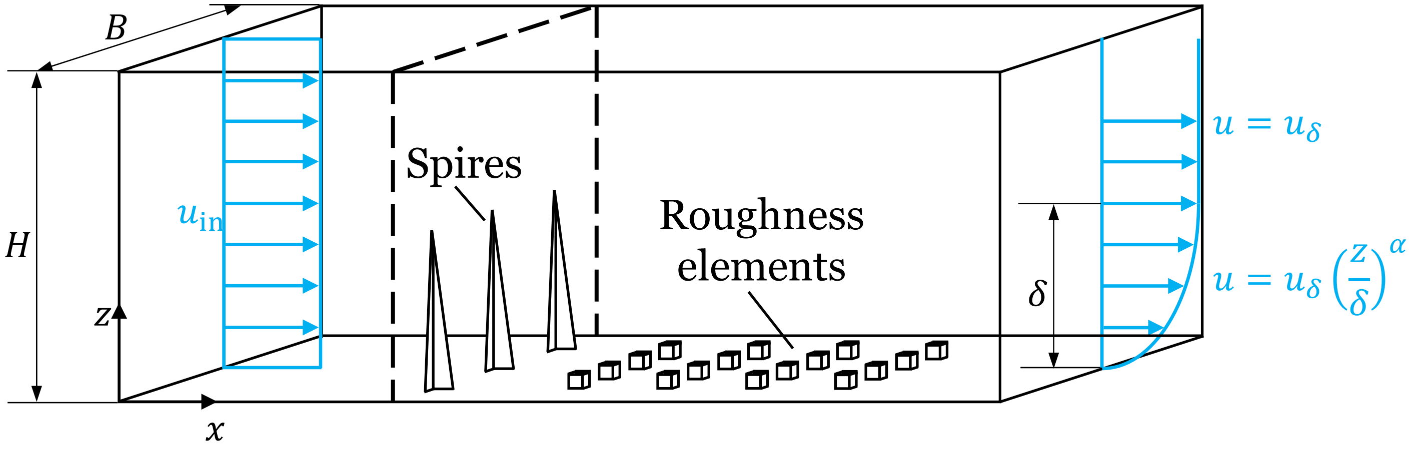


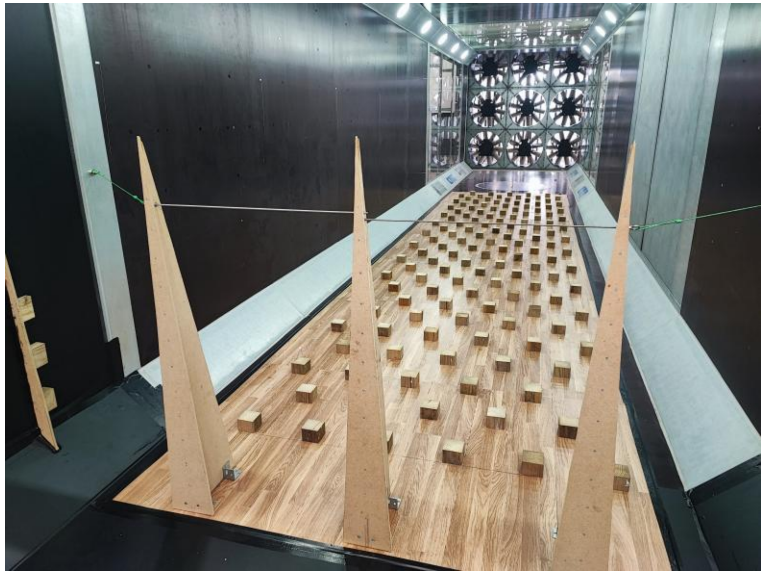






- ABL characterization
  - Eurocode: Category III
  - Irwin method → roughness elements and spires
  - **Two wind tunnels**: UPV (CMT) and UPM (IDR)





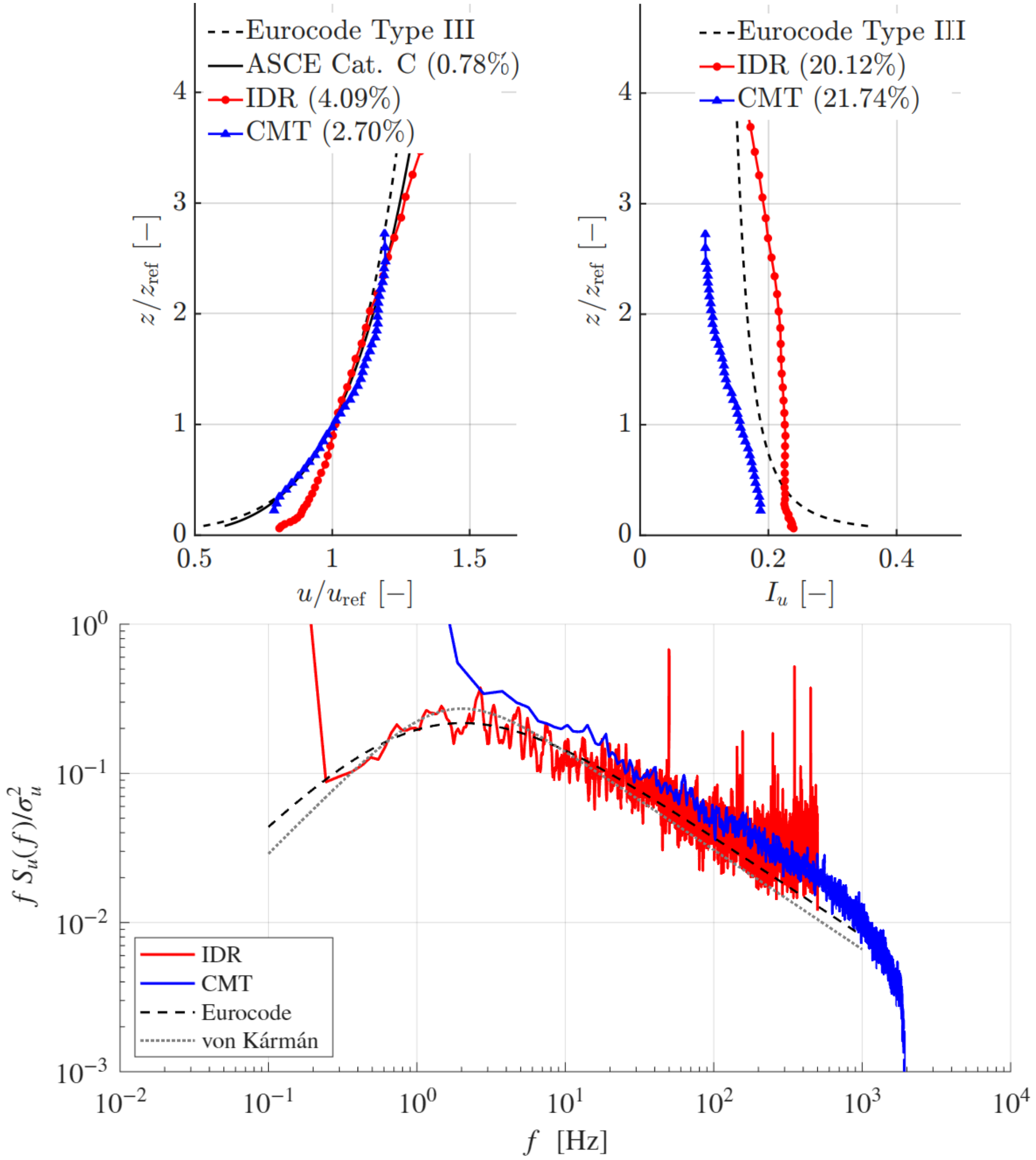
- Cross-validation in two wind tunnels
  - Velocity profile:

$$u = C\,(z/z_0)^{\alpha}$$

  - Turbulence intensity profile:

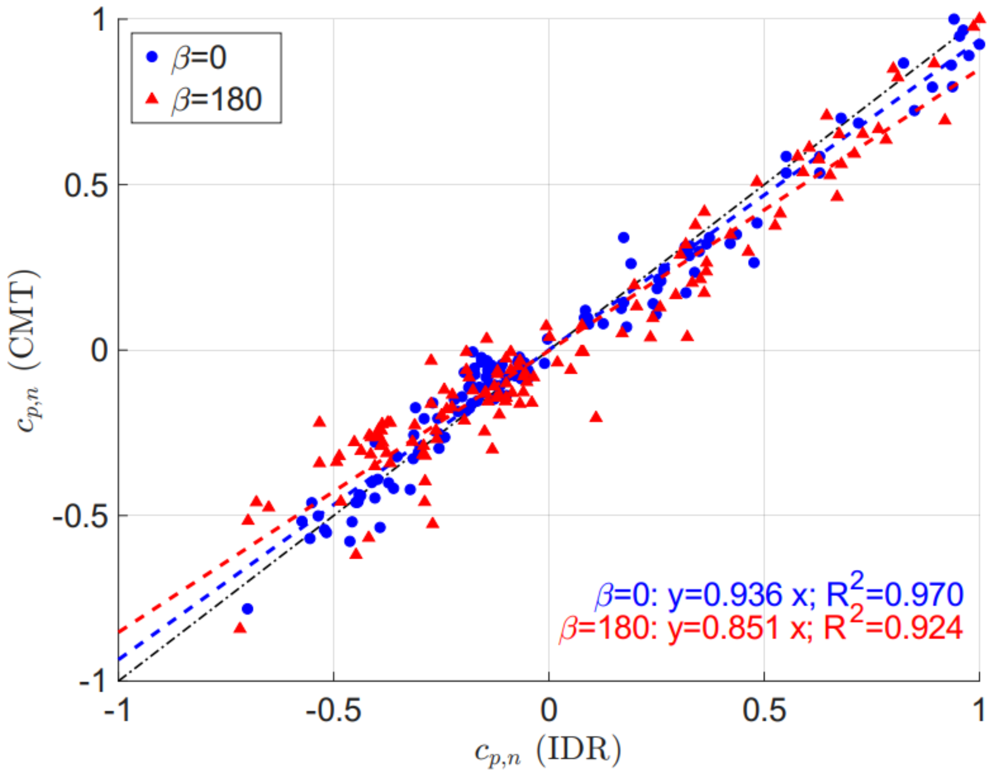
$$I_u = \frac{1}{\ln(\frac{z}{z_0})}$$

  - Power Spectral Density (PSD) plot
    - Analysis of high-energy eddies
    - Energy cascade
    - Minimum and cut-off frequency
    - Noise floor



- Cross-validation in two wind tunnels
  - Good accuracy for different angles of incidence
  - Small influence of I_u difference on the mean c_p
  - Higher dispersion in wake regions

$$c_p = \frac{p - p_{ref}}{q_{ref}} = \frac{p - p_{ref}}{0.5\ \rho\ U_{ref}^2}$$



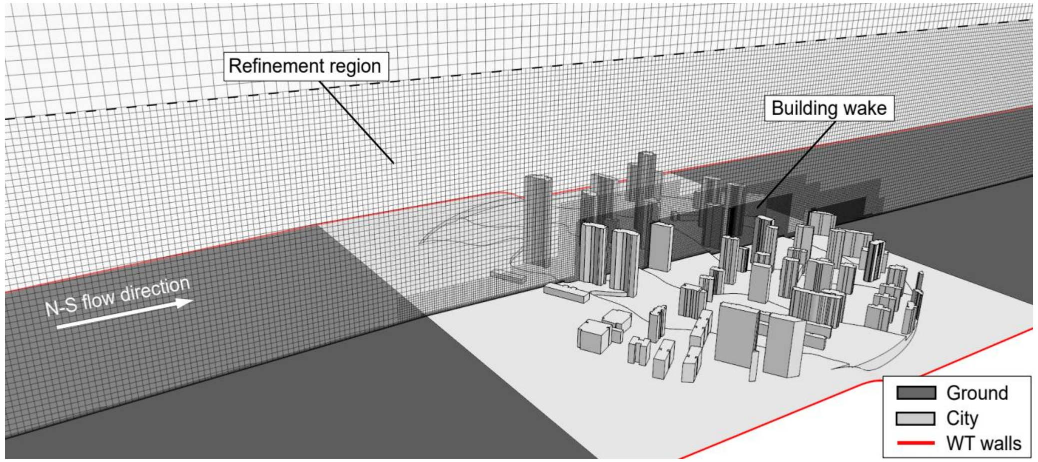
0. Introduction

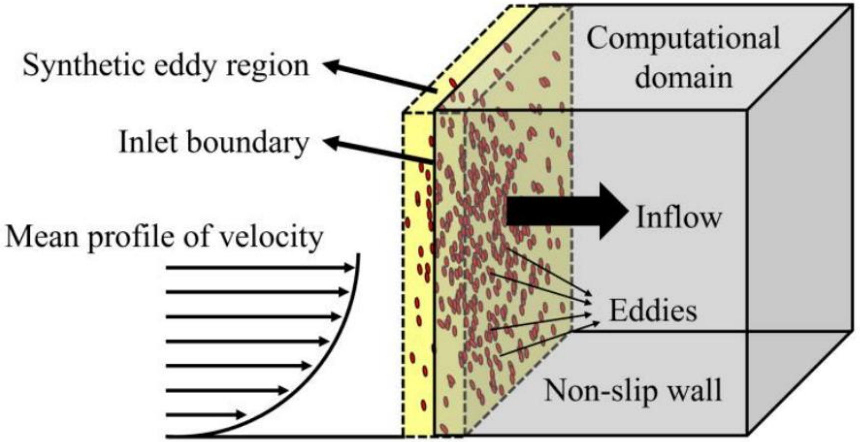
1. Experimental studies

2. **Numerical simulations**
    - **Numerical set-up**
    - **LES Quality assessment**
    - **Results: RANS vs LES**
    - **CFD validation**
    - **Turbulent structures**

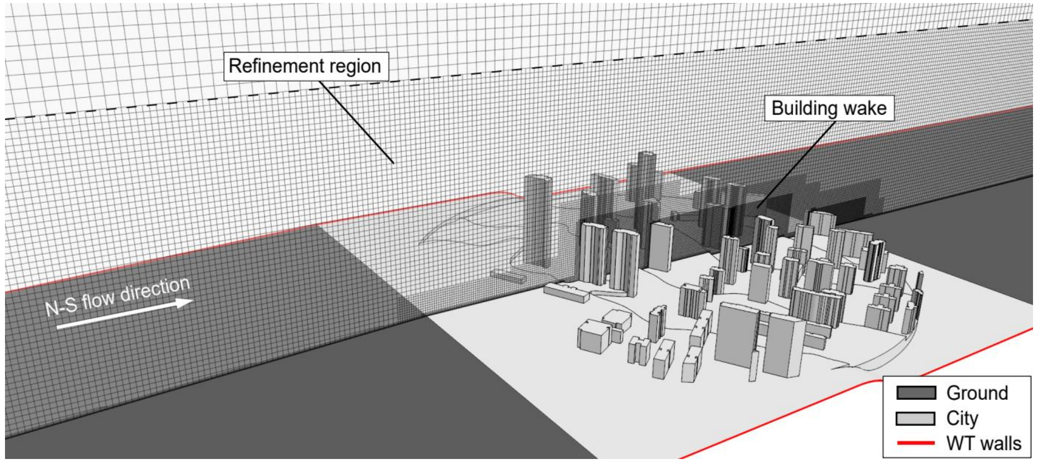
3. Future work

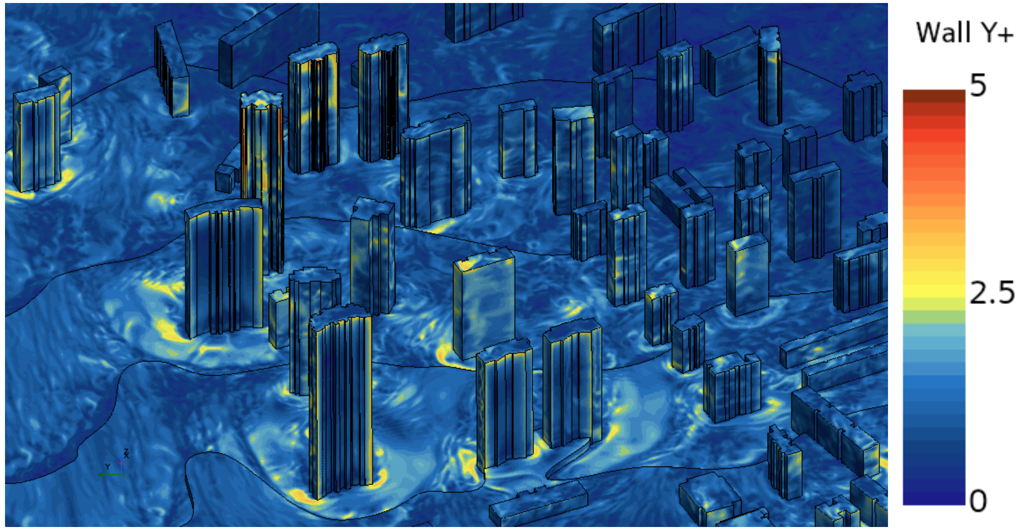
❖ Numerical set-up
  ○ Domain: IDR wind tunnel, 2.2x2.2 square cross-section
  ○ Trimmed mesher (for LES, 60M cells)
  ○ Boundary conditions:
    • Wall no-slip condition
    • Pressure outlet
    • RANS: inlet u and k profiles from experimental data (ϵ from local equilibrium estimation)
    • LES: SEM, requires u, Reynolds stresses, and integral length scale (Taylor frozen turbulence hypothesis)





- Numerical set-up
  - RANS:
    - Realizable $k - \epsilon$ method
    - SIMPLE pressure–velocity coupling
    - Spatial discretization: 2nd order
  - LES:
    - Near-wall resolution ($y^+ \approx 1$)
    - Spatial scheme: bounded central differencing
    - Temporal discretization: 2nd order implicit
    - Time step $2 * 10^{-4}$ s, total time ~55 τ_{conv}
    - Wall-Adapting Local Eddy-viscosity (WALE) subgrid-scale model
  - Costs: 6-8 (RANS) vs 67 (LES) wall-clock hours



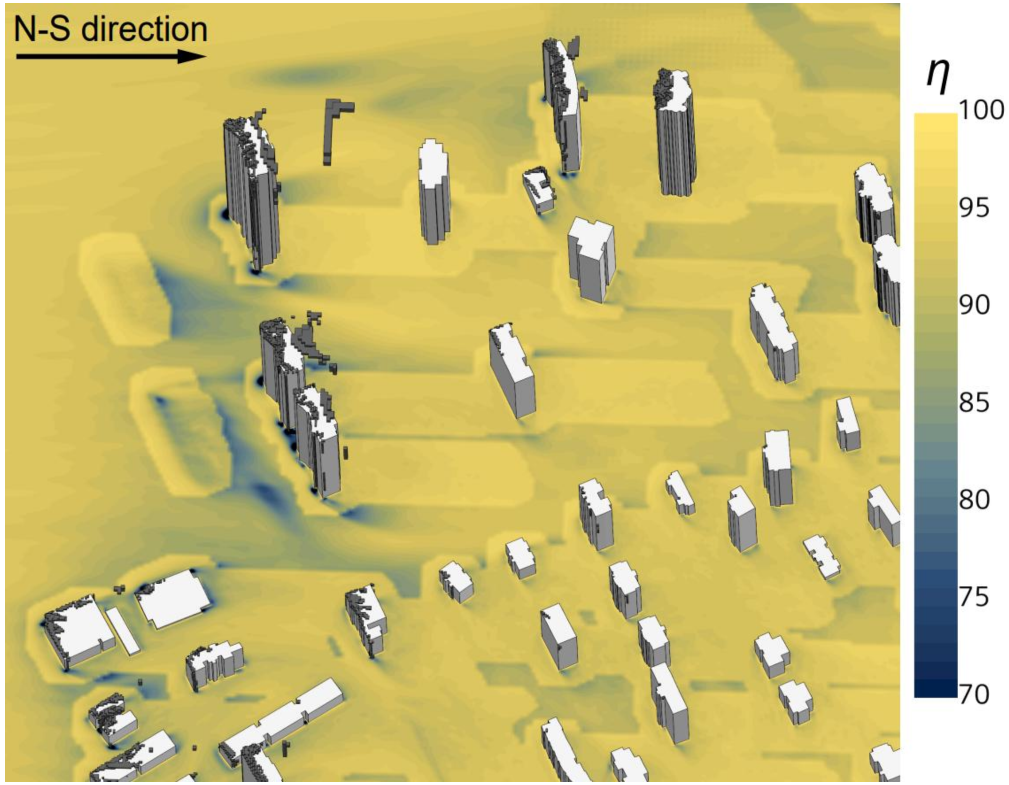


LES quality assessment

- Turbulence kinetic energy ratio

$$\eta = \frac{k_c}{k_{total}} = \frac{k_c}{k_{SGS} + k_c}$$

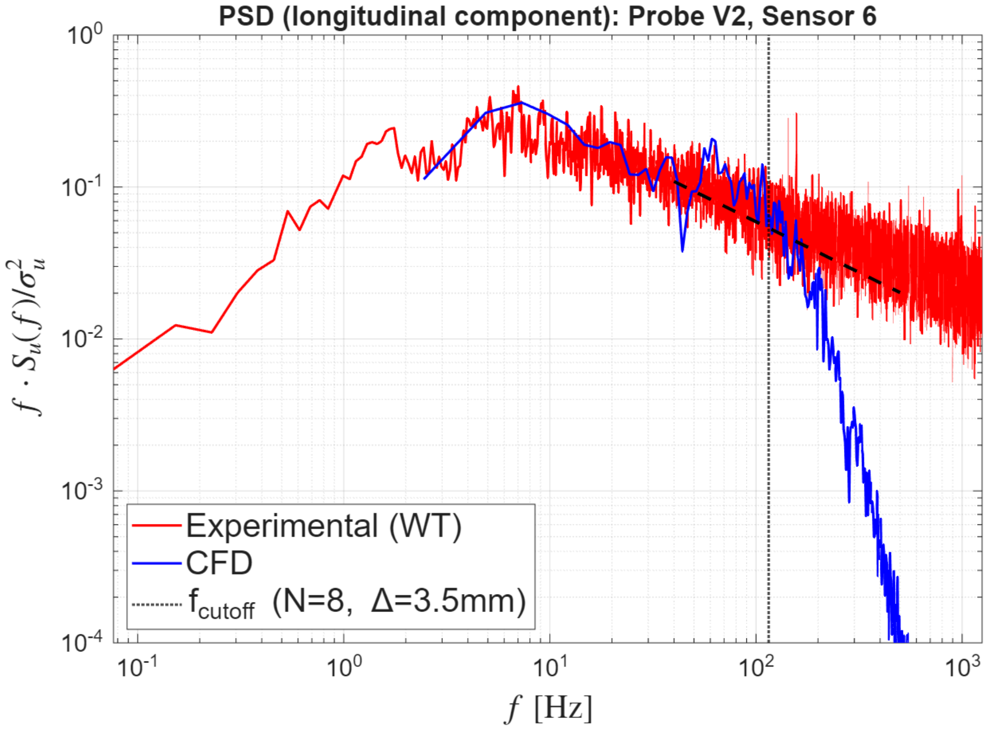
- Mesh resolution acceptance above a threshold (usually η > 80%)
- Low-resolution cells on building edges and first-line buildings

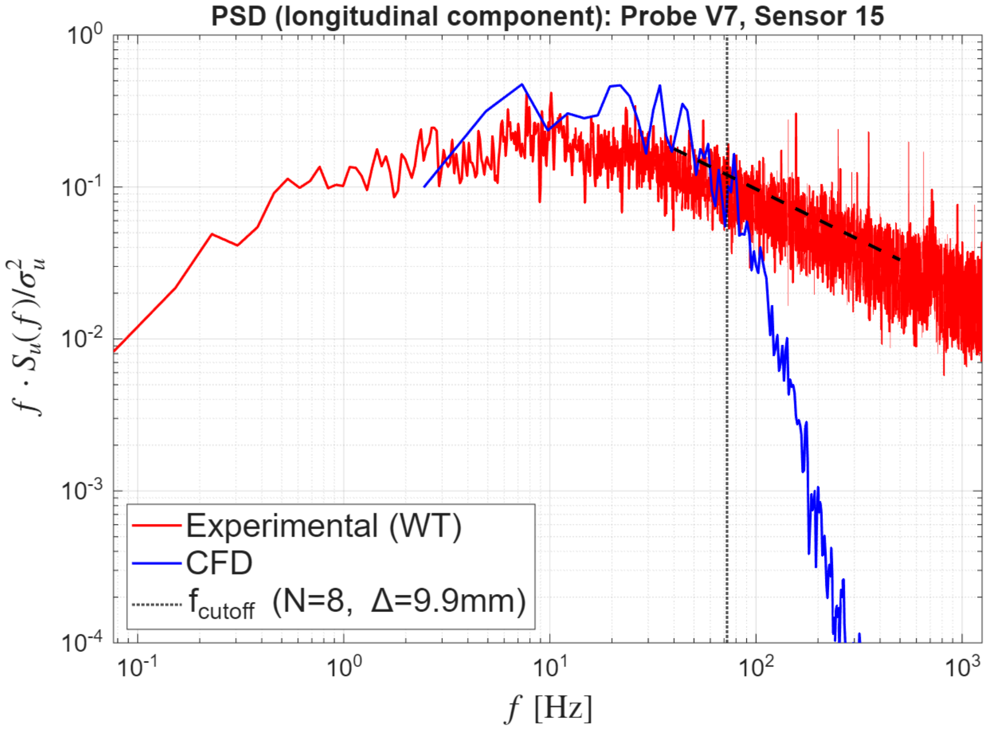


- LES quality assessment
  - PSD of velocity longitudinal component
    - Analysis of cutoff frequency: cutoff wavenumber within the inertial subrange
    - Taylor's frozen turbulence hypothesis

$$f_{cutoff} = \frac{u}{N\,\Delta_c}$$

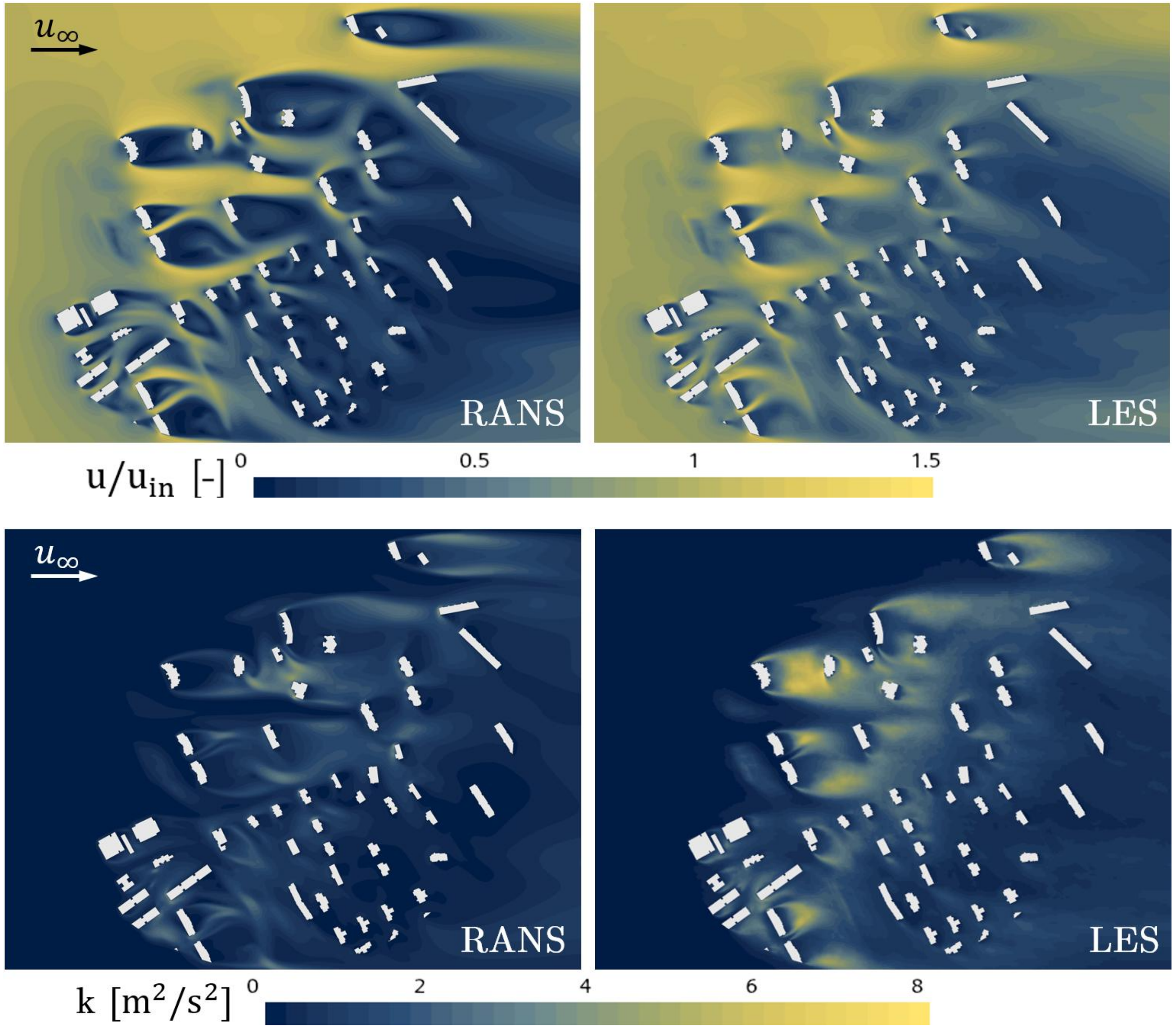
$$E(k) \propto \epsilon^{2/3} k^{-5/3}$$





❖ Results

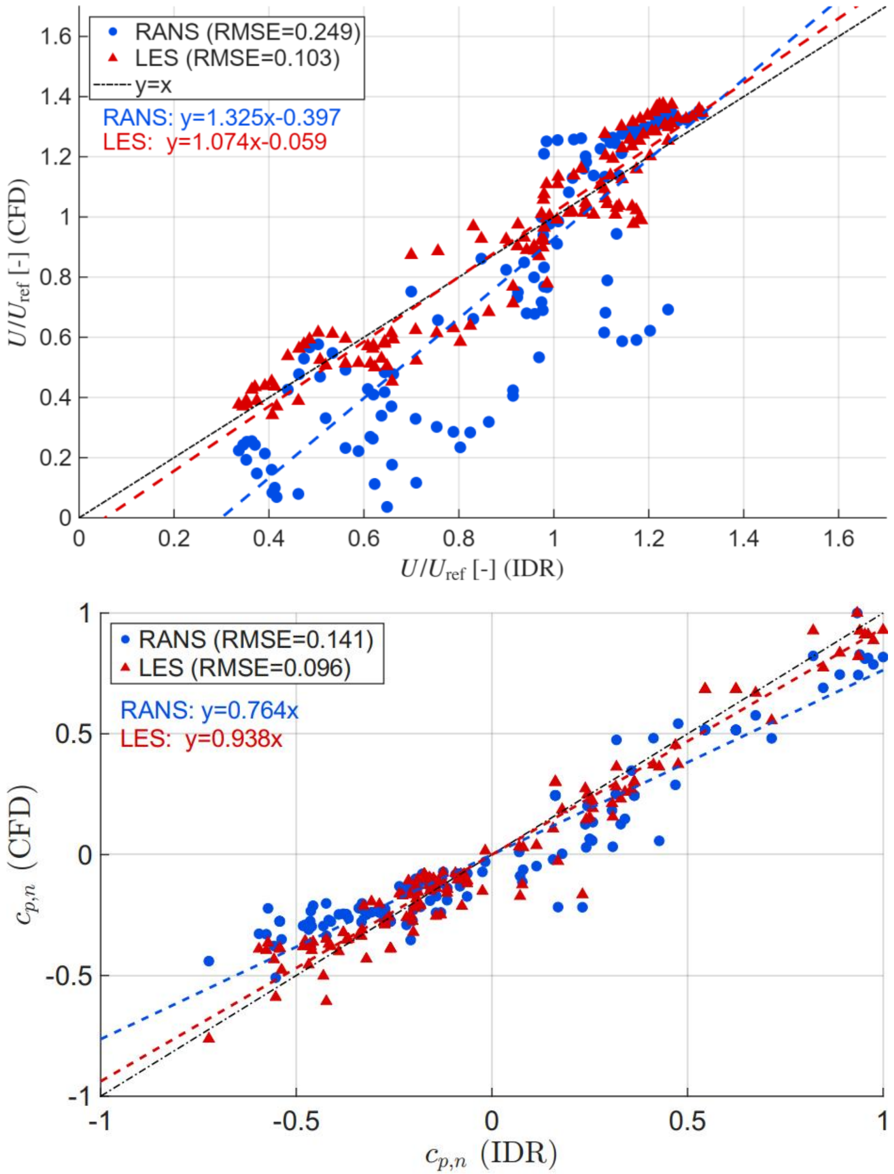
- RANS:
  - Underprediction of velocity in the wake
  - Underprediction of the turbulent kinetic energy
  - Suppresses turbulent unsteady effects
- LES
  - Greater accuracy for extreme conditions
  - Unsteady shear-layer detachment resolution



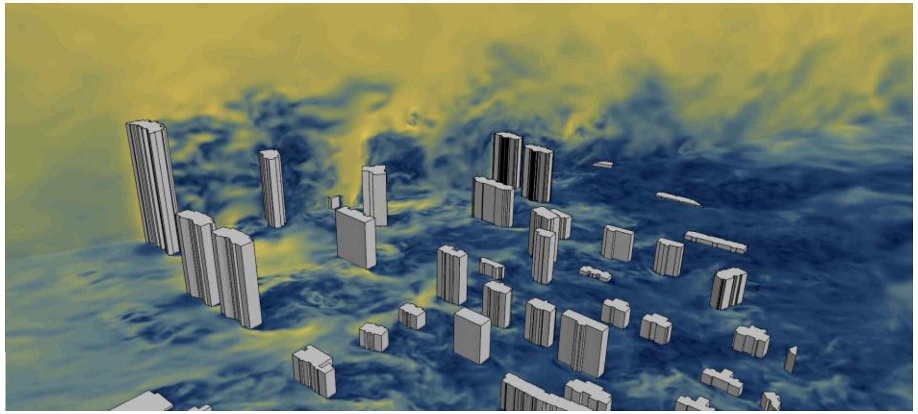
- CFD validation: mean u and c_p
  - RANS
    - High velocity scatter against experimental data
    - Average $RMSE_u$ = 0.249, $RMSE_{c_p} = 0.141$
    - Local errors exceed 80%
  - LES
    - Average $RMSE_u$ = 0.103, $RMSE_{c_p} = 0.096$
    - More accurate peak values
    - Maximum local error of 30%

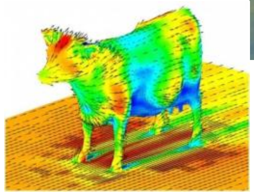
$$c_p = \frac{p - p_{ref}}{q_{ref}} = \frac{p - p_{ref}}{0.5\,\rho\,U_{ref}^2}$$

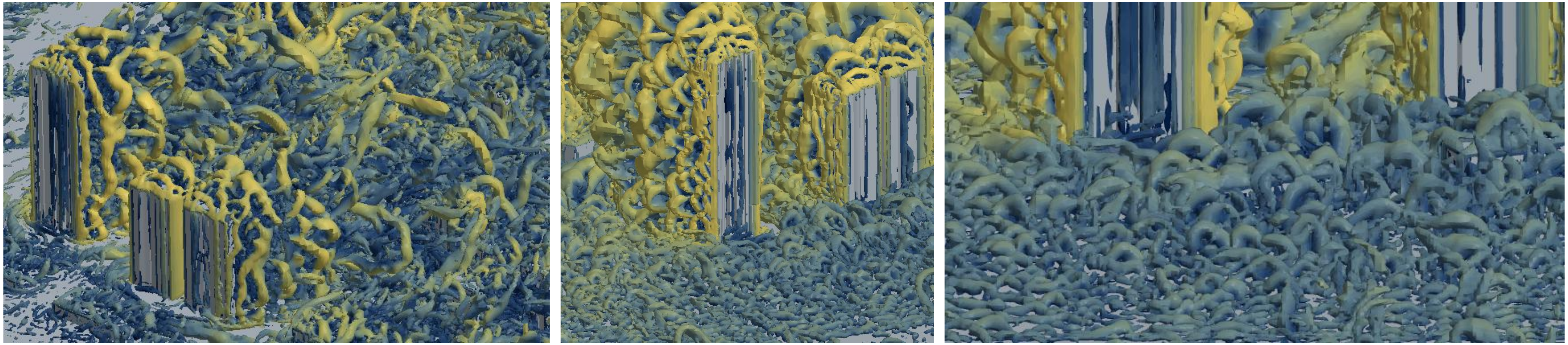
$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{\left(\phi_i - \phi_i^{exp}\right)^2}{N}}$$



- Turbulence structures
  - Q-criterion: $Q = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2)$
  - Analysis of coherent structures
  - Great to compare characteristic lengths with drone size
  - Better for CFD (Colors For Directors)







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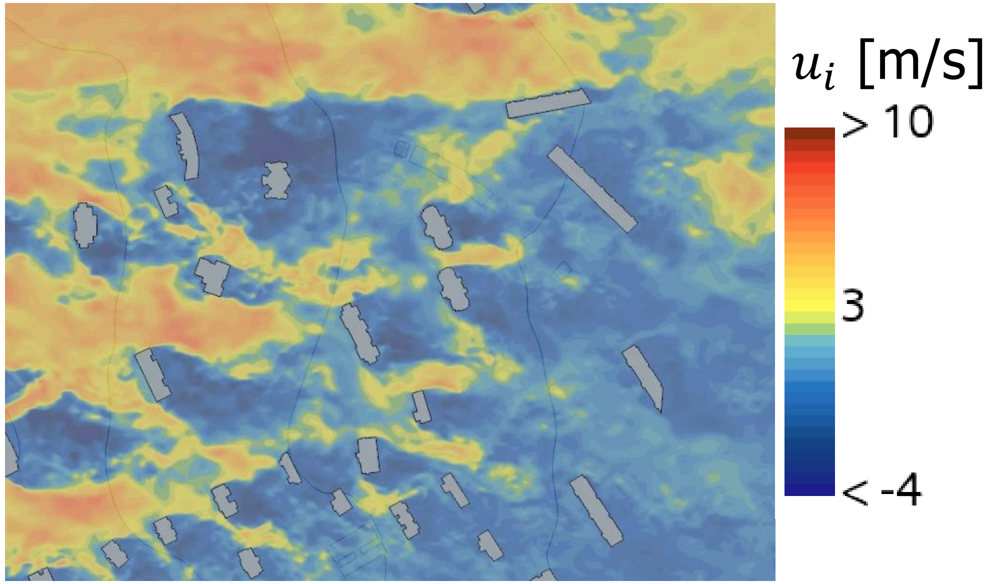
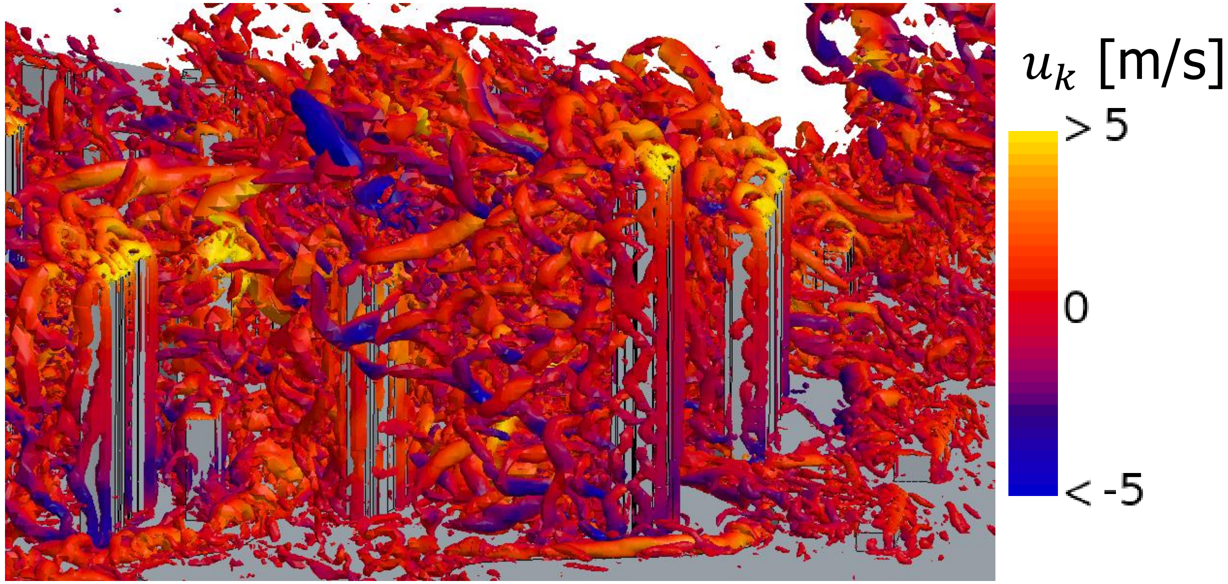
3. **Future work**

- Interesting for **future internships/TFM topics**! ☺
  - Inflow turbulence generation methods
  - Meshing strategy for trajectory optimization methods
  - POD/ROM and flow reconstruction
  - ML?





Thank you for your attention

"An expert is a man who has made all the mistakes which can be made in a narrow field"

– Niels Bohr

Contact: César Sánchez Aguado
csanagu@upv.edu.es

ATTENDANCE