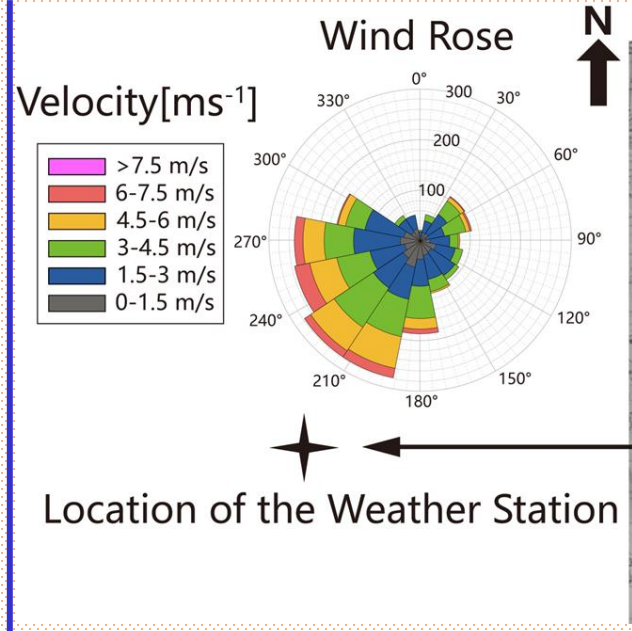
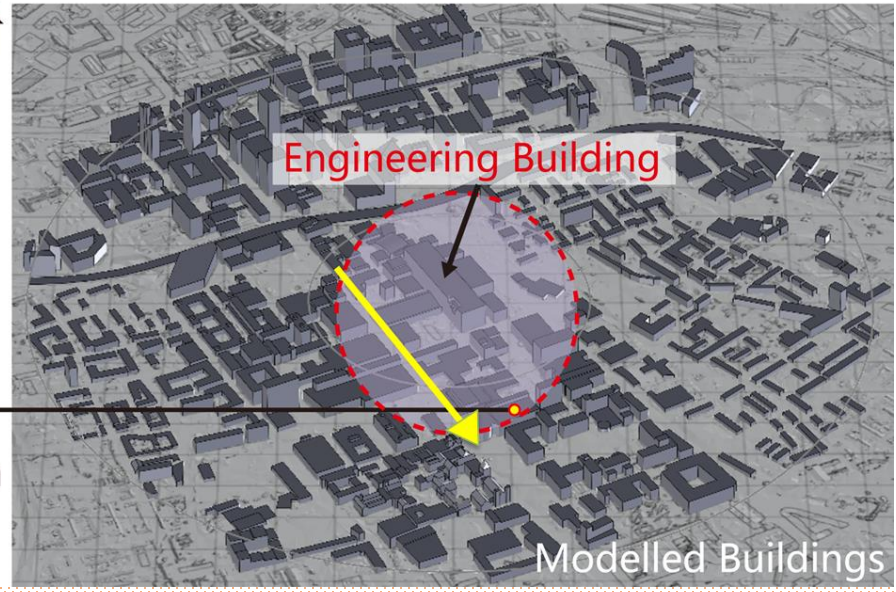
The University of Manchester

Uncertainty Quantification and Data Analysis in Urban Wind Flows





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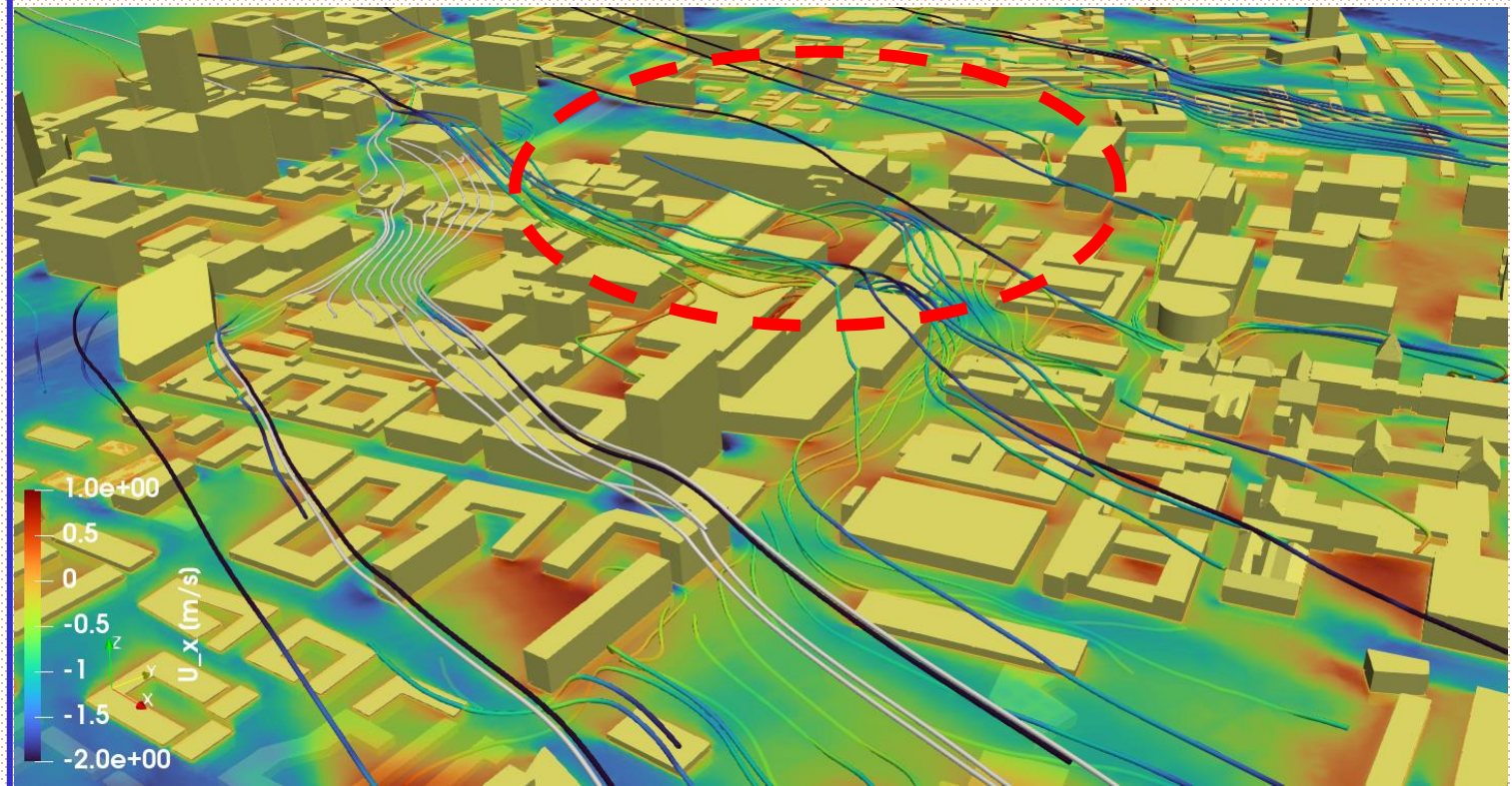
Department of Fluid and Environment

The University of Manchester



Workshop in Data-driven methods, machine learning and optimization in fluid mechanics.

31 March 2022

Main objective

Towards Real-time prediction of wind patterns in urban environments and the potential uncertainties due to both physical and numerical parameters

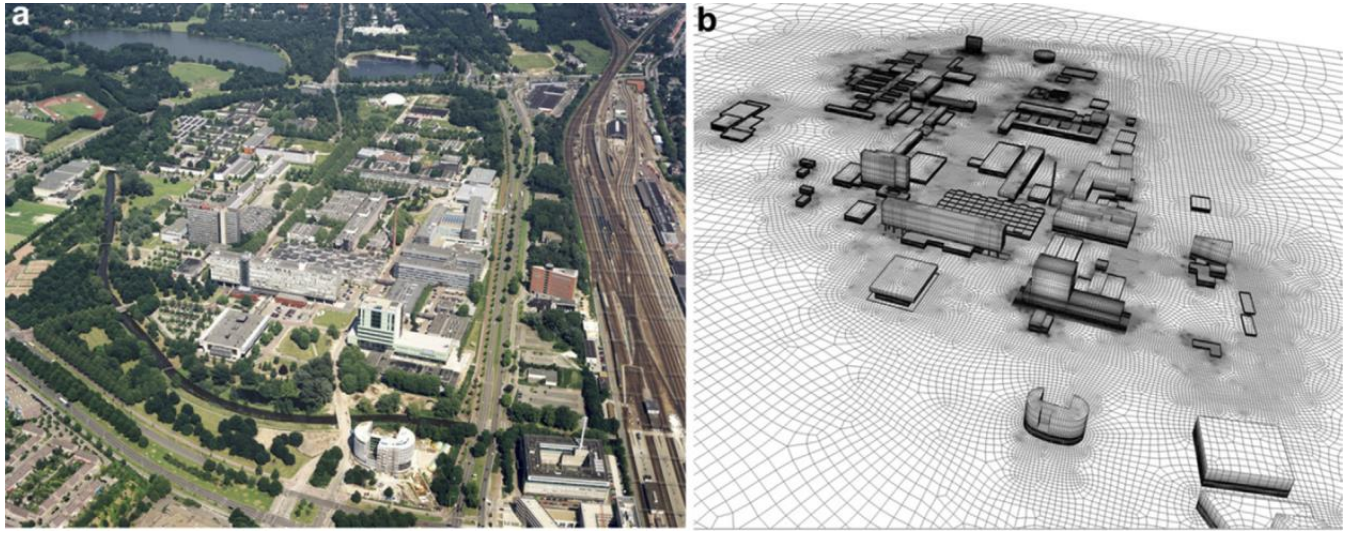
- Geometrical simplifications (ignoring roughness elements such as cars and vegetation)
- Extents of computational domain
- Level of fidelity of turbulence simulation

- Idealized (yet realistic) boundary conditions
- Turbulence closure model/ turbulence approach
- Grid resolution

Some Applications

- ❑ Wind energy
- ❑ Pedestrian comfort
- ❑ Pollutant dispersion
- ❑ Ventilation strategies
- ❑ Deployment of wind turbines
- ❑ Design of sustainable and resilient urban areas

Geometrical simplifications



Actual **Simplified**

Focus of this talk

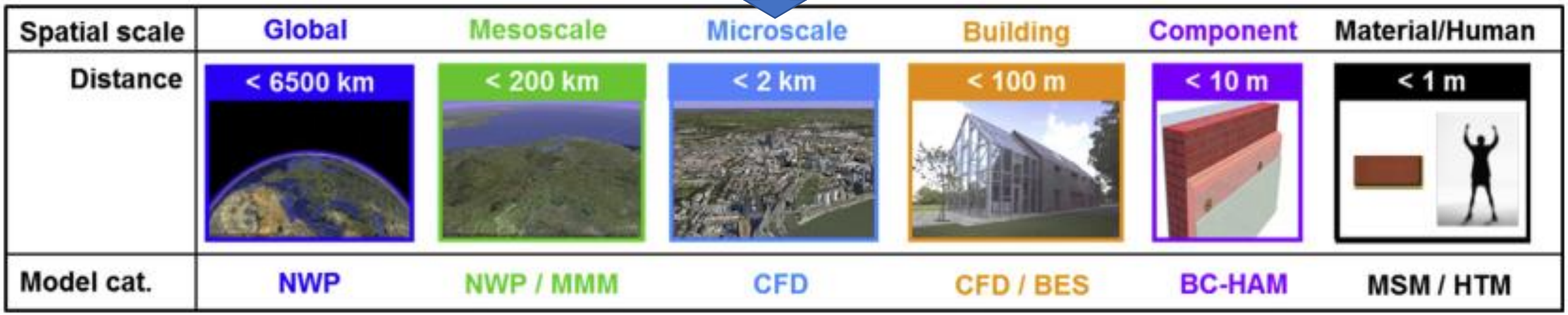
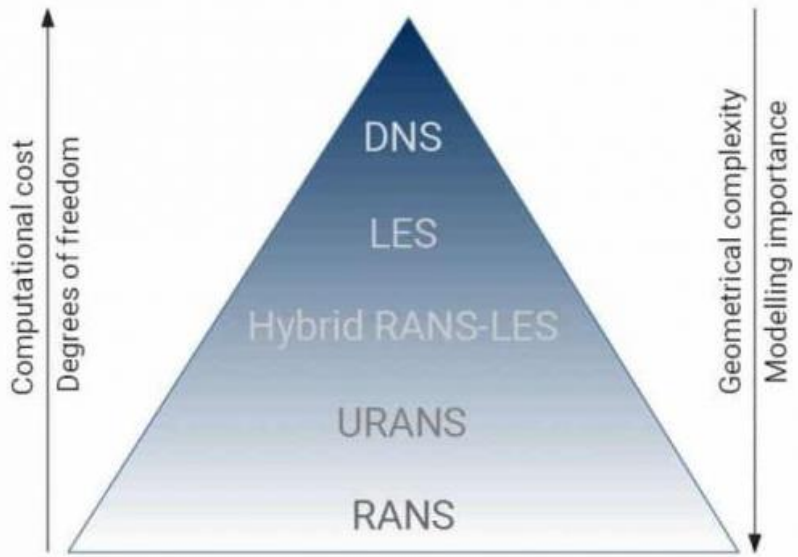


Fig. 1. Schematic representation of the six spatial scales in urban physics

- **NWP** = Numerical Weather Prediction;
- **MMM** = Mesoscale Meteorological Model;
- **CFD** = Computational Fluid Dynamics;
- **BES** = Building Energy Simulation;
- **BC-HAM** = Building Component - Heat, Air, Moisture transfer;
- **MSM** = Material Science Model;
- **HTM** = Human Thermophysiology Model.

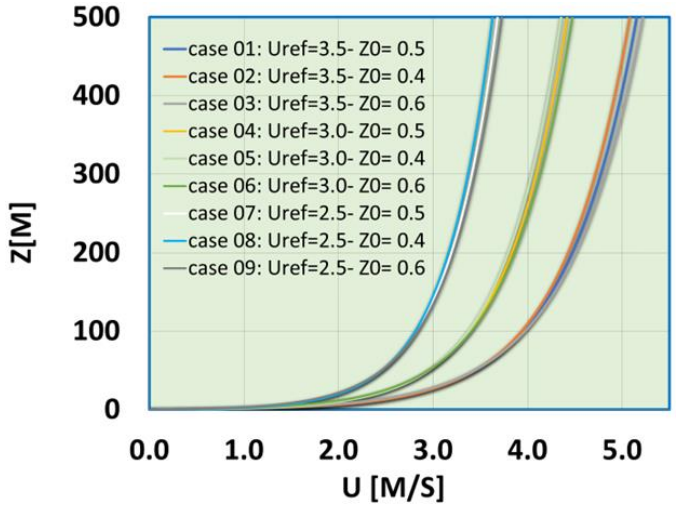


Why RANS?

- ❑ LES is at least one order of magnitude more expensive than RANS. If validation is required, it can be two orders of magnitude time consuming than RANS!
- ❑ Limited number of best practice guidelines for LES
- ❑ Generating proper inflow boundary conditions
- ❑ Convergence problem due to the high order discretization schemes that are not diffusive
- ❑ Near wall treatment (using a hybrid approach or like DES or wall functions)
- ❑ We need a lot of CFD simulations for UQ (different uncertain parameters)

Effect of windspeed and aerodynamic roughness

Appropriate BCs for CWE using the k-ε @ inlet

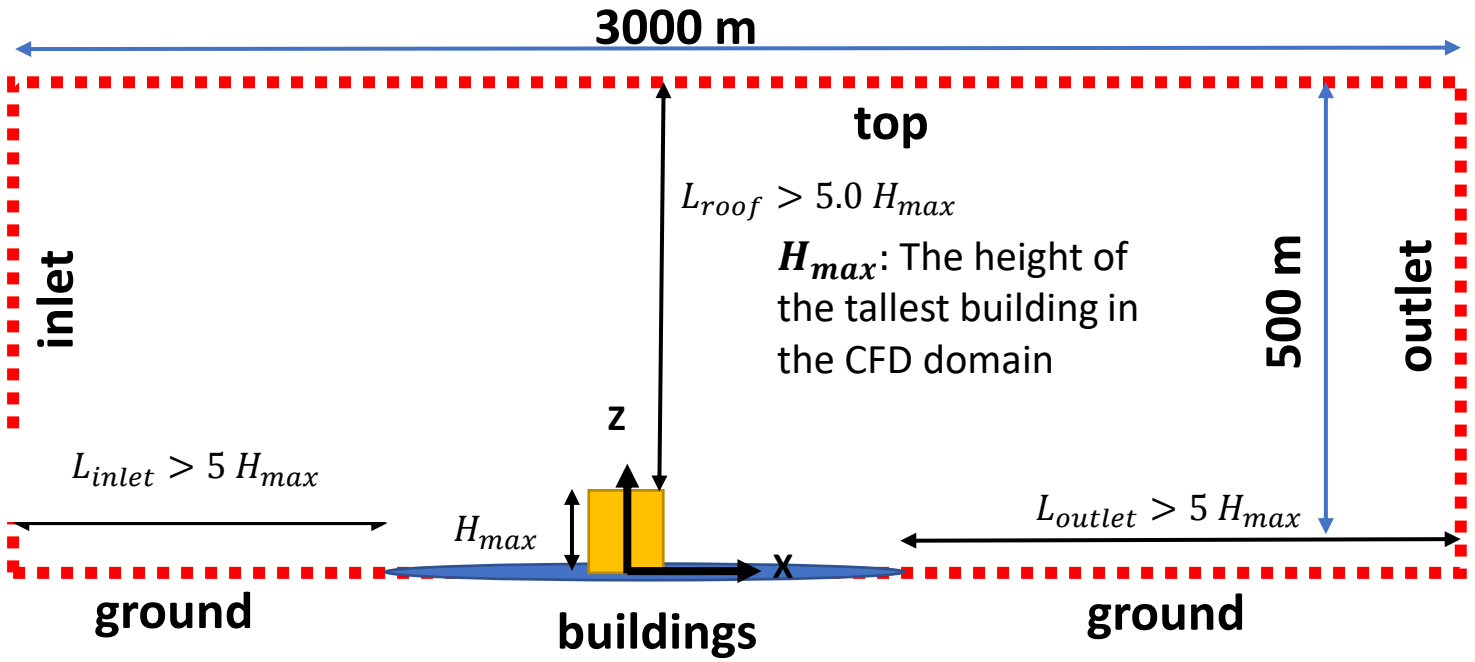


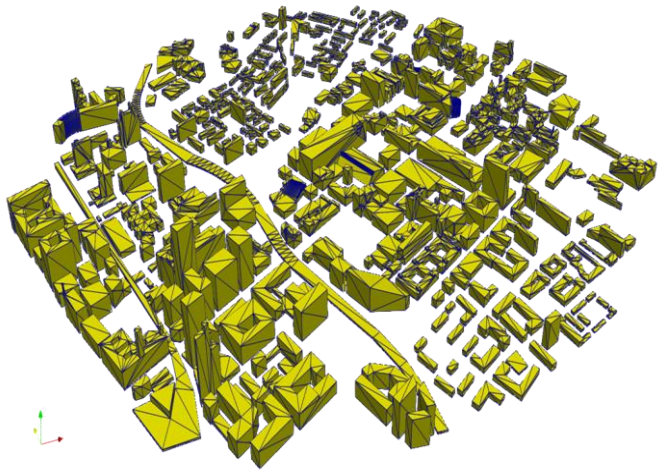
$$U(z) = \frac{u^*_{ABL}}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right)$$

$$k(z) = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}}$$

$$\varepsilon(z) = \frac{u^{*3}_{ABL}}{\kappa(z + z_0)}$$

Fig. 1. Inlet velocity profile





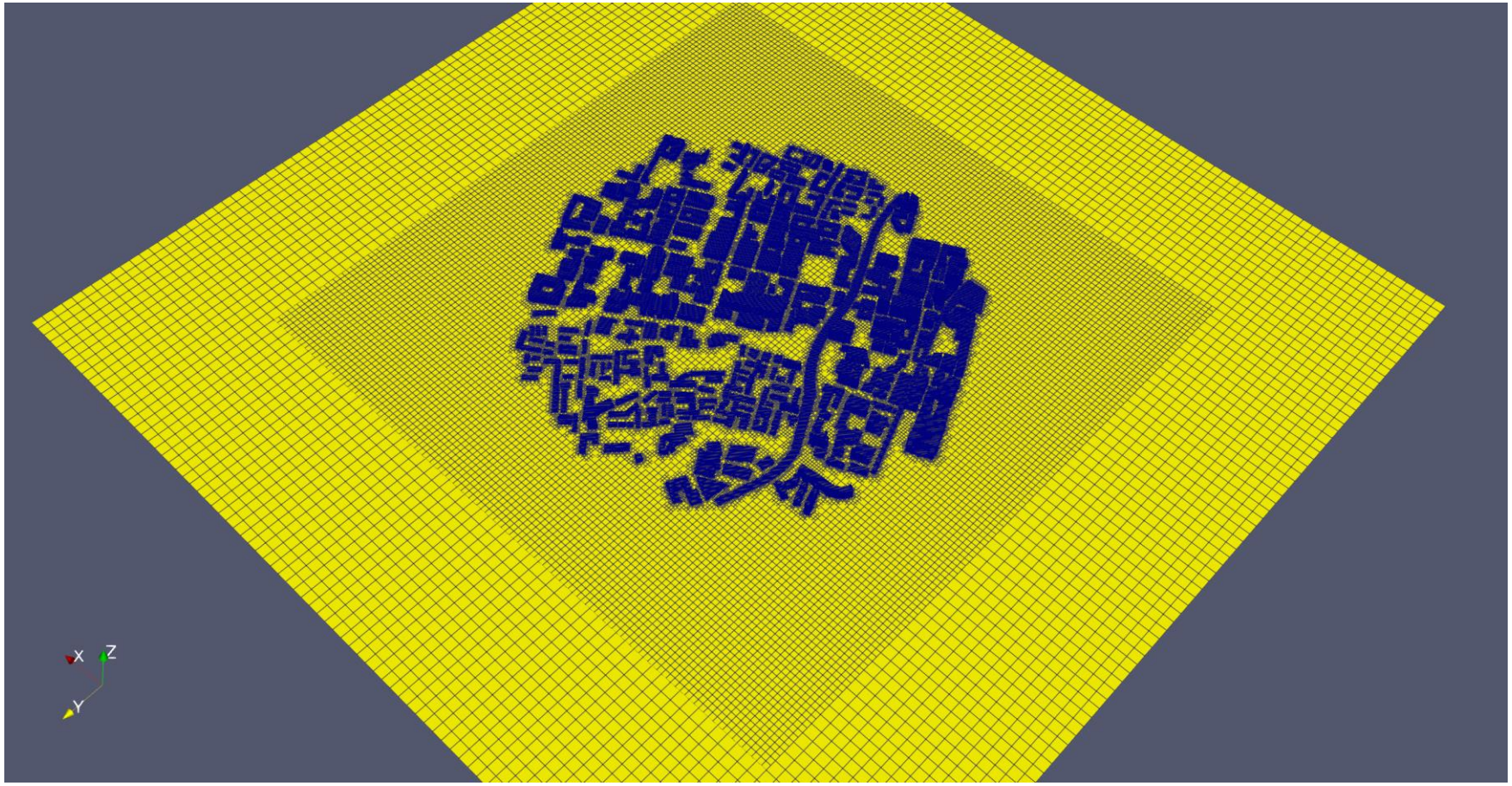
Best practice guidelines:

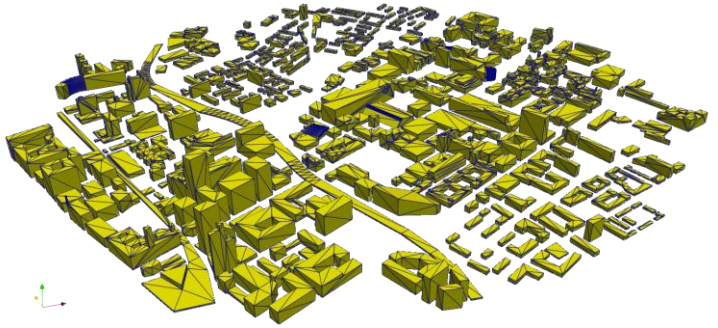
- ❑ **COST Action 732**
- ❑ **AIJ (2008)**

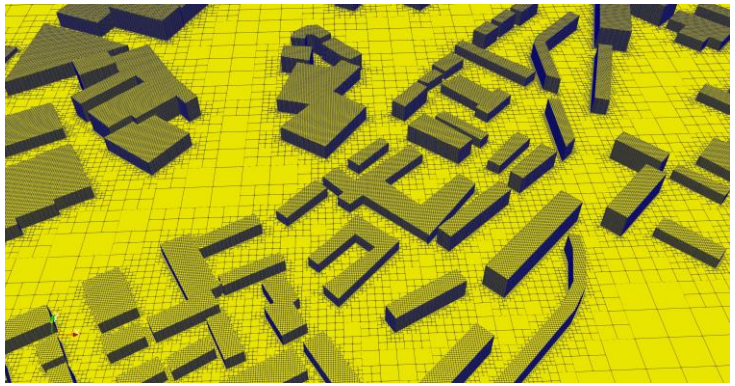
Fig. 2. Schematic representation of computational domain

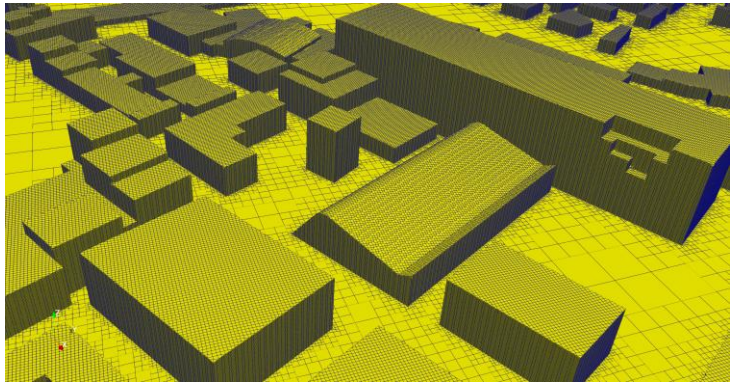
Grid Generation

Coarse mesh (8 million)
Fine mesh (90 million)
Extra fine mesh (0.5 billion)

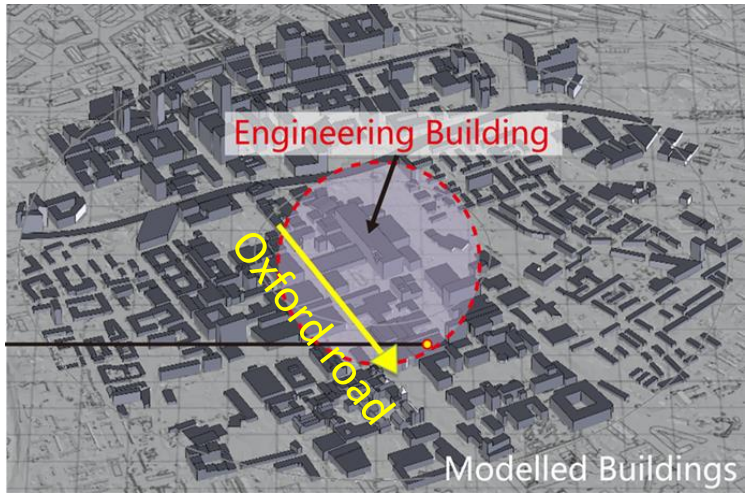


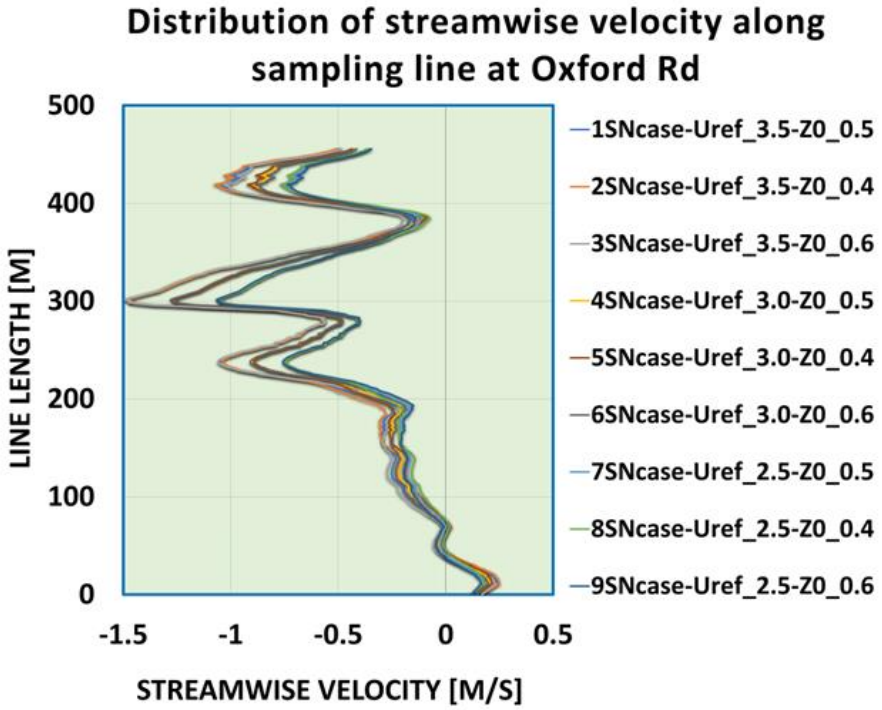




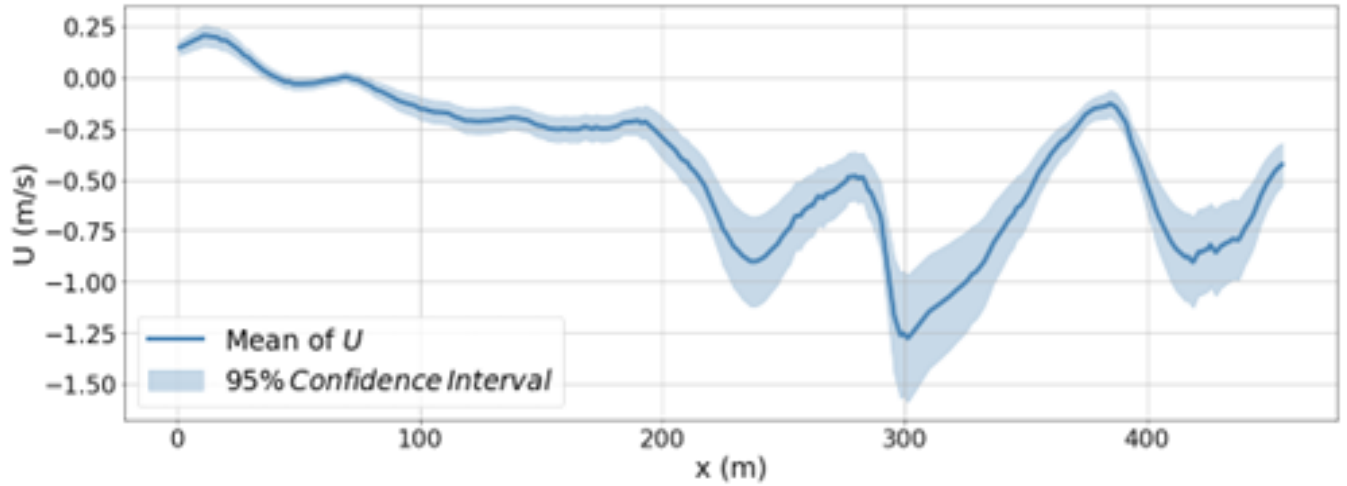


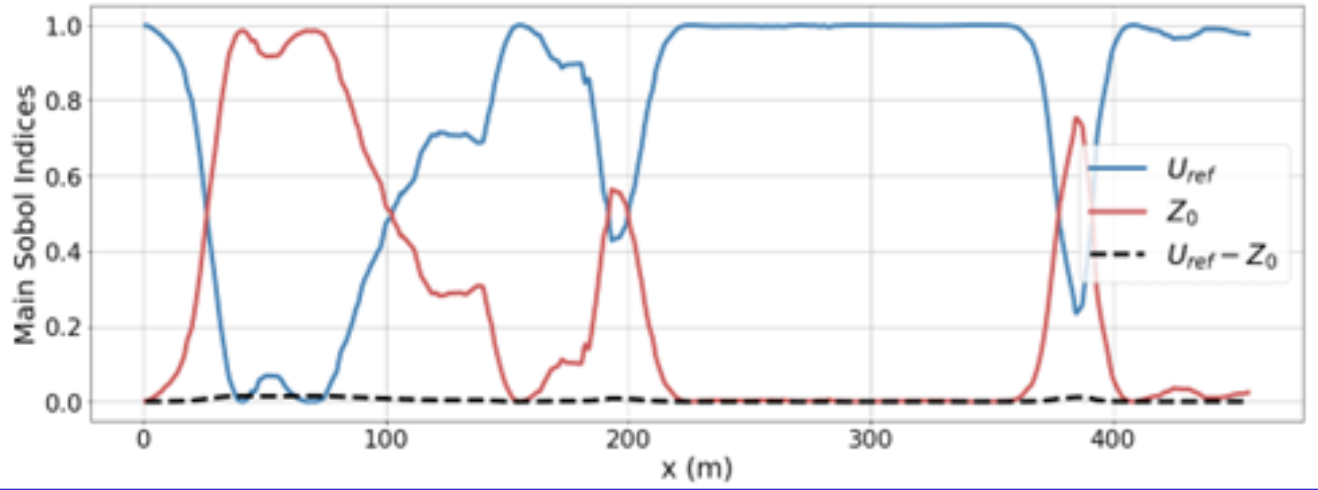
Effect of windspeed and aerodynamic roughness





Uncertainty Propagation & Global Sensitivity Analysis

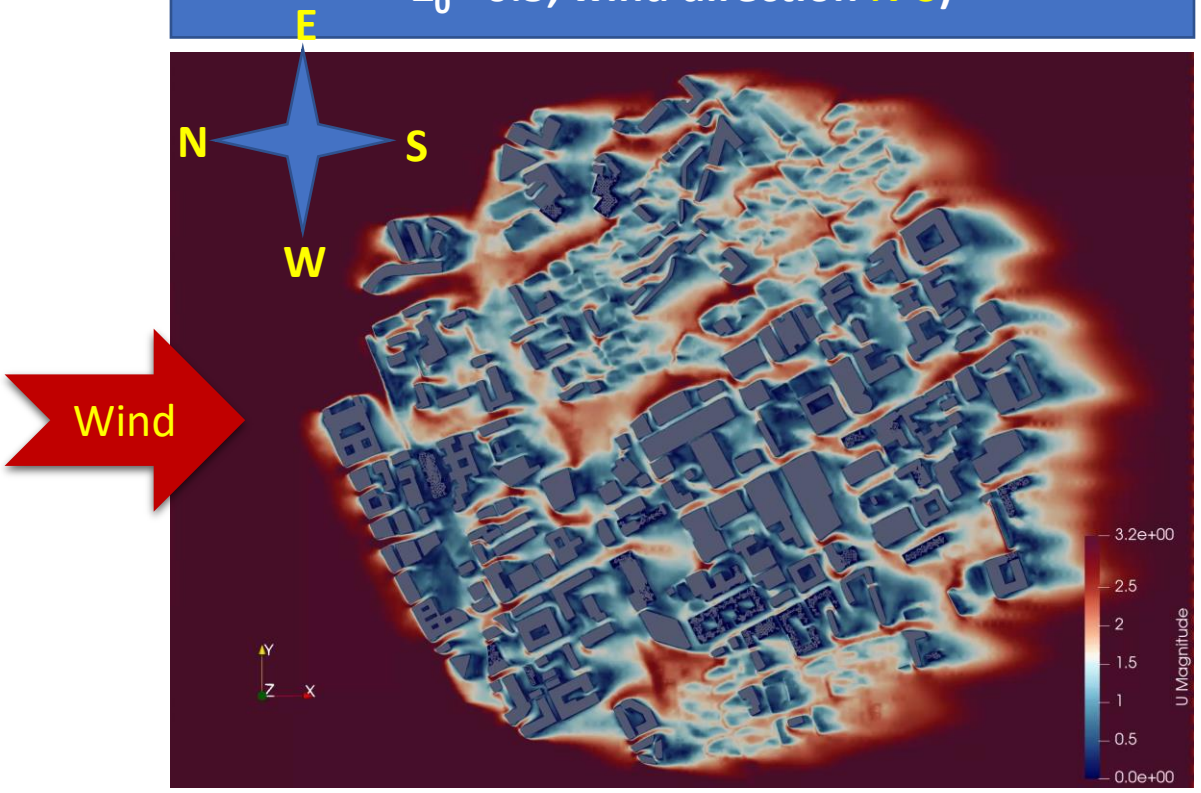




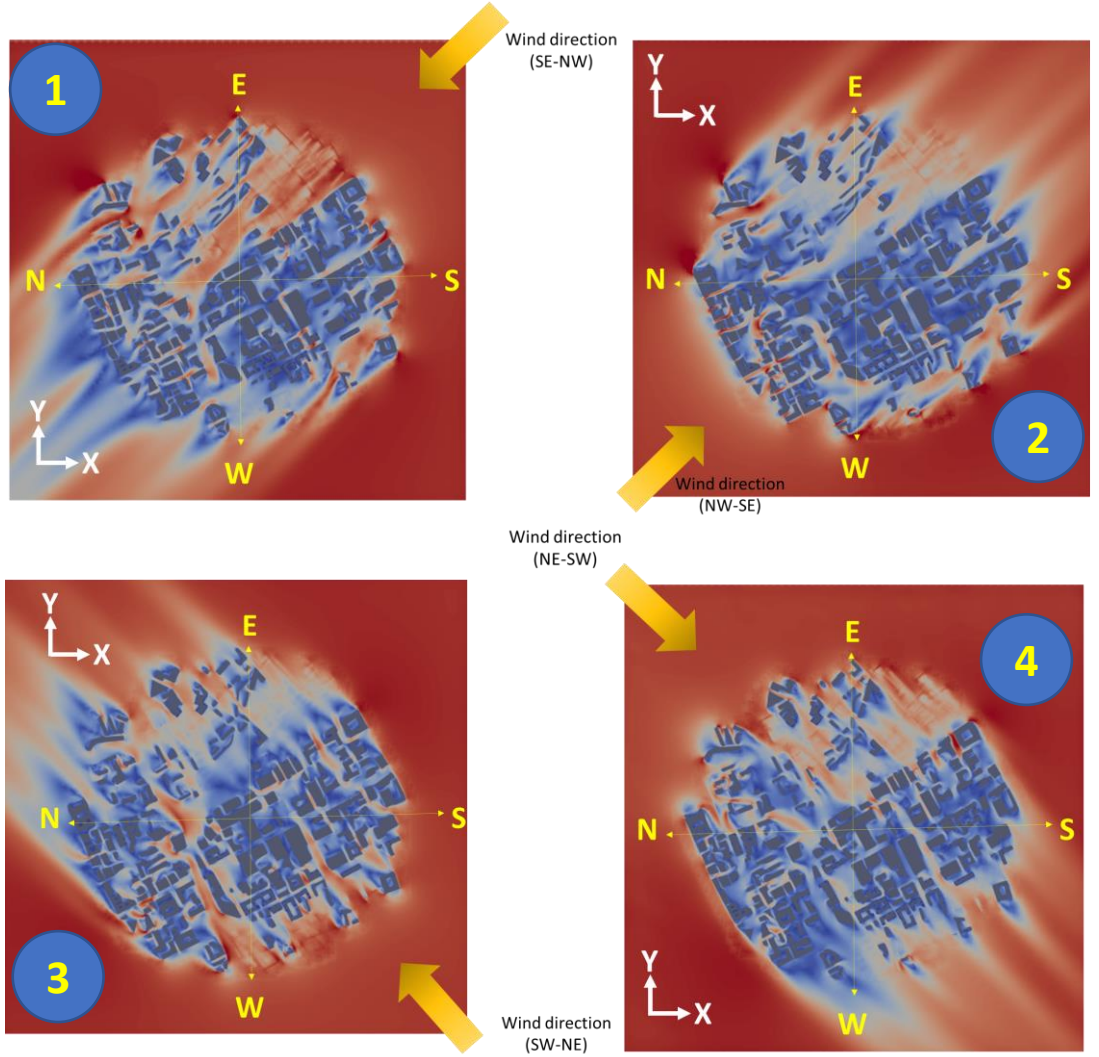
Effect of windspeed and wind direction

- Preliminary RANS (k-epsilon) results at Height=10m from the ground level.
- The animation shows how initial conditions are washed out from the computational domain and steady-state results are achieved.

Distribution of velocity for case 01 (Uref = 3.5; Z_0= 0.5, wind direction N-S)



Distribution of velocity for different wind directions 1:SE-NW; 2: NW-SE; 3: SW-NE; 4: NE-SW)



Effect of windspeed and wind direction

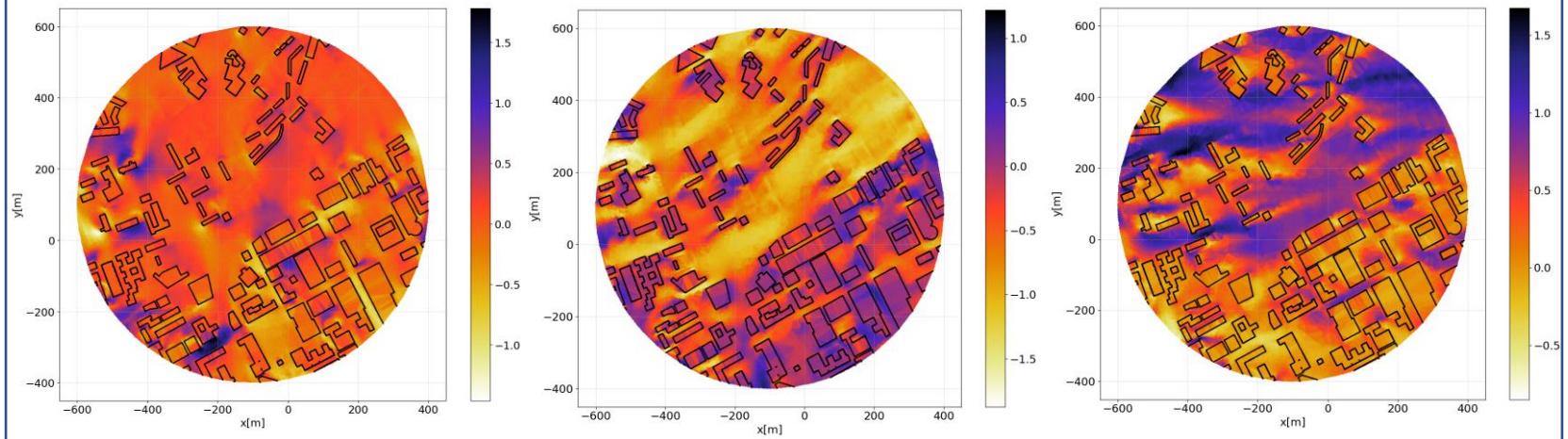
case	wind direction	wind angle	velocity magnitude [m/s]
1	S-N	180	3
2	SW-NE	225	3
3	W-E	270	3
4	NW-SE	315	3
5	N-S	0	3
6	NE-SW	45	3
7	E-W	90	3
8	SE-NW	135	3
9	S-N	180	2.5
10	SW-NE	225	2.5
11	W-E	270	2.5
12	NW-SE	315	2.5
13	N-S	0	2.5
14	NE-SW	45	2.5
15	E-W	90	2.5
16	SE-NW	135	2.5
17	S-N	180	3.5
18	SW-NE	225	3.5
19	W-E	270	3.5
20	NW-SE	315	3.5
21	N-S	0	3.5
22	NE-SW	45	3.5
23	E-W	90	3.5
24	SE-NW	135	3.5

Data Analysis

- 24 RANS simulations (8 wind angles and 3 wind speeds),
- Simulations by OpenFOAM.
- Without loss of generality, the streamwise velocity is taken as the quantity of interest in the following slides.

Objectives:

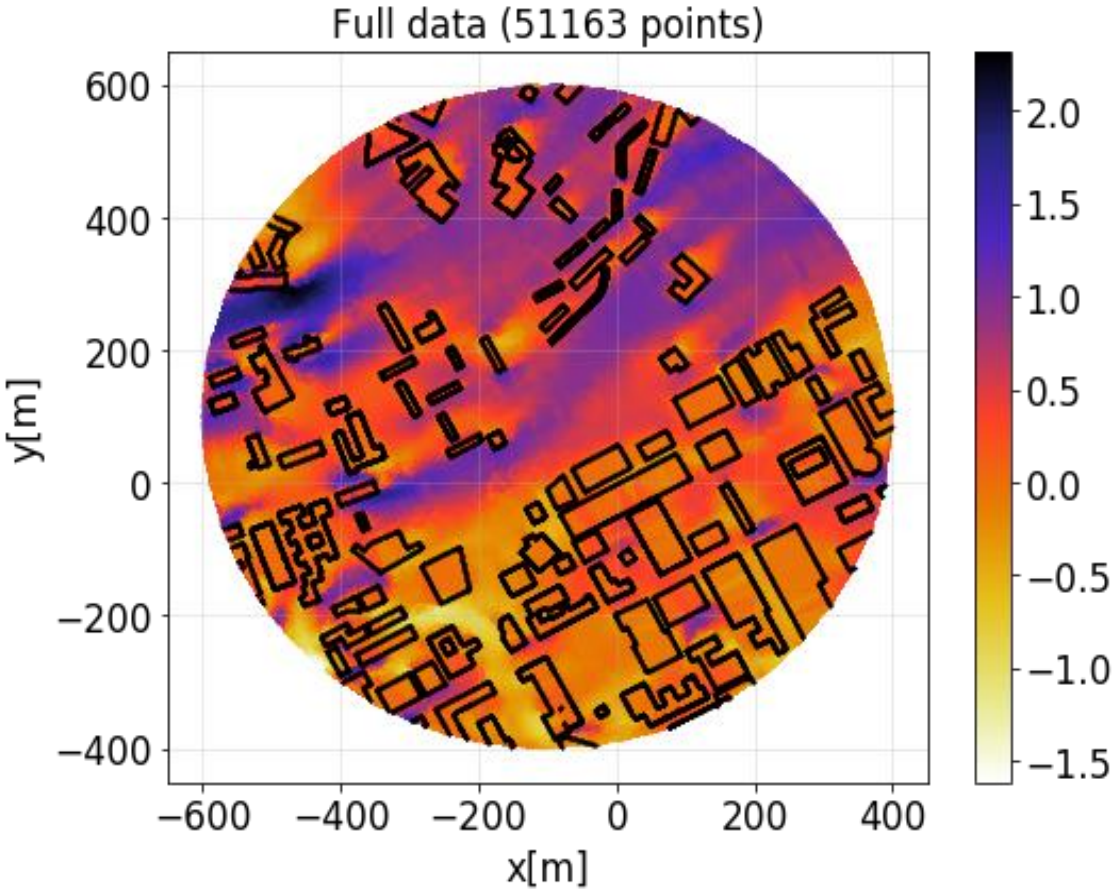
- Surrogate construction,
- Prediction of the flow fields,
- Global Sensitivity Analysis.

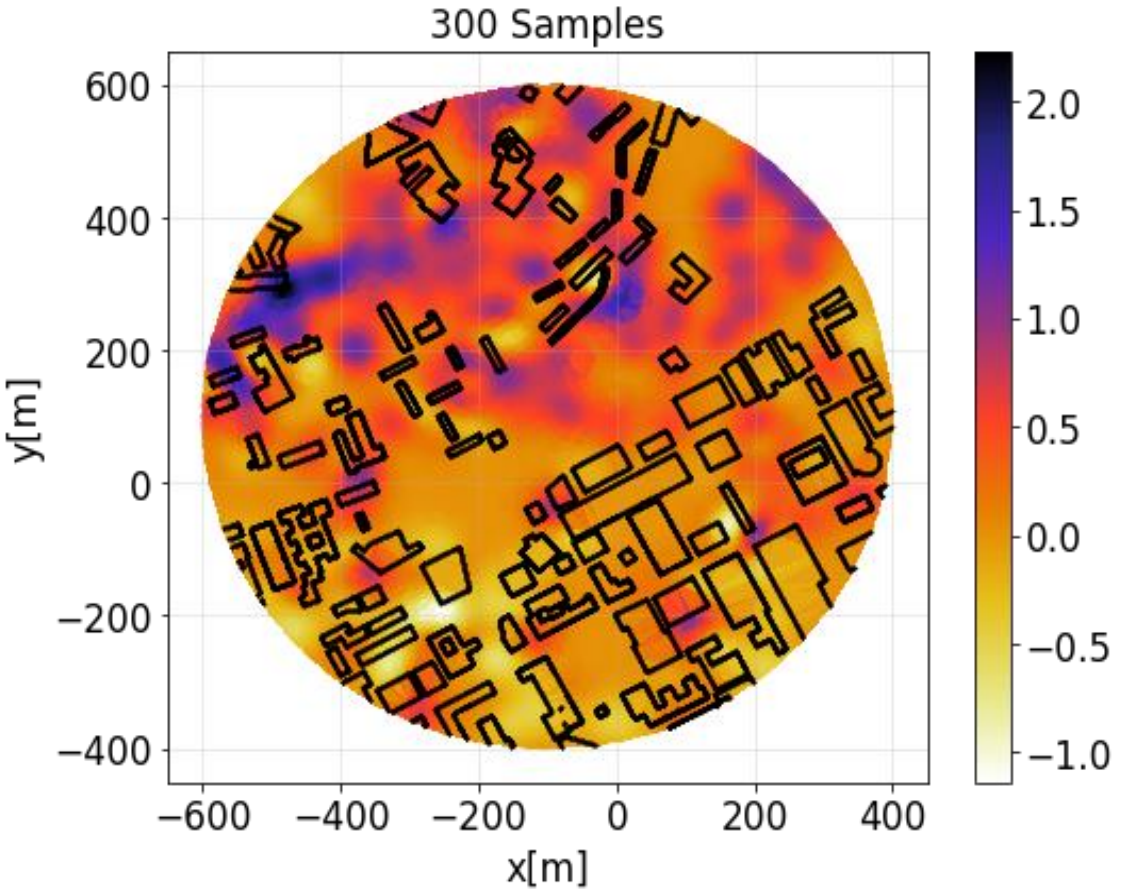


Surrogates for flow quantities over the space of x,y

- **Left**: Full dataset with 51k points in the x-y domain.
- **Right**: The GP surrogate adaptively updated in 170 rounds with 10 adaptive samples per round. The adaptive samples are taken at locations with highest uncertainty in the posterior predictive of the GP.

Starting set of samples: randomly selected





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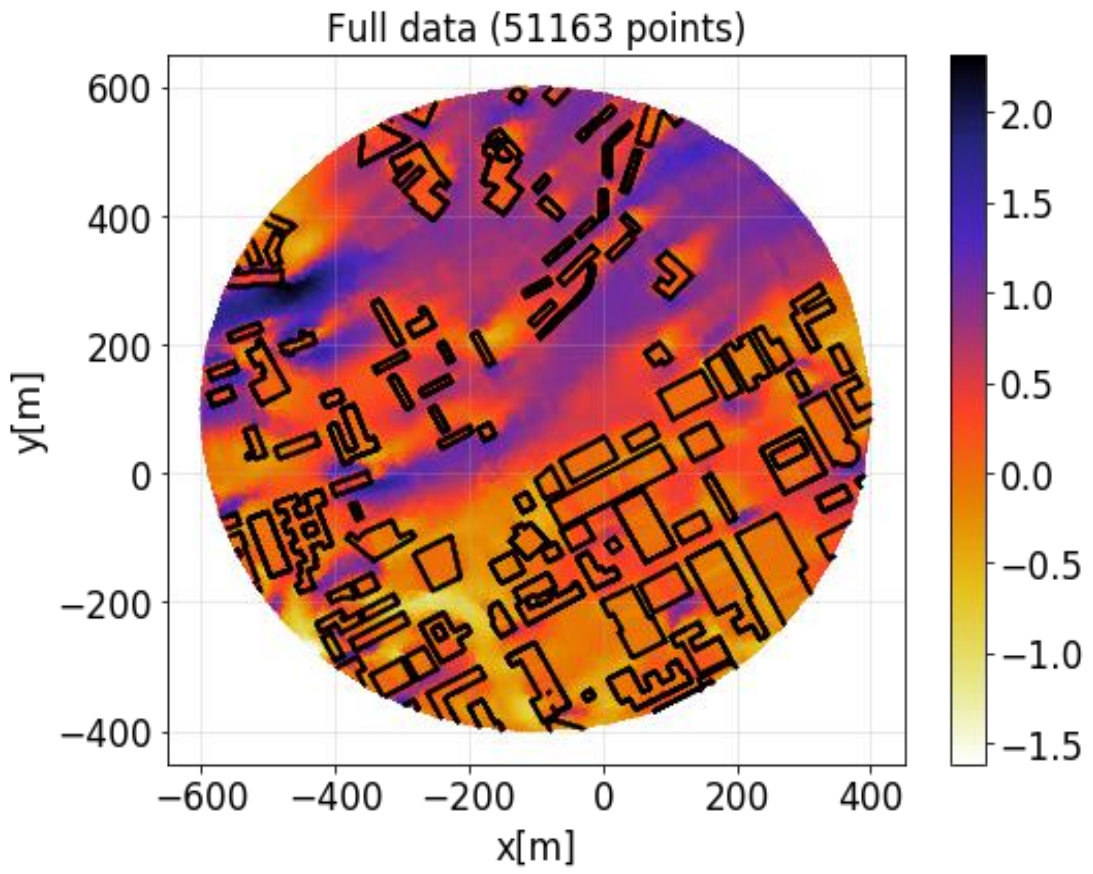

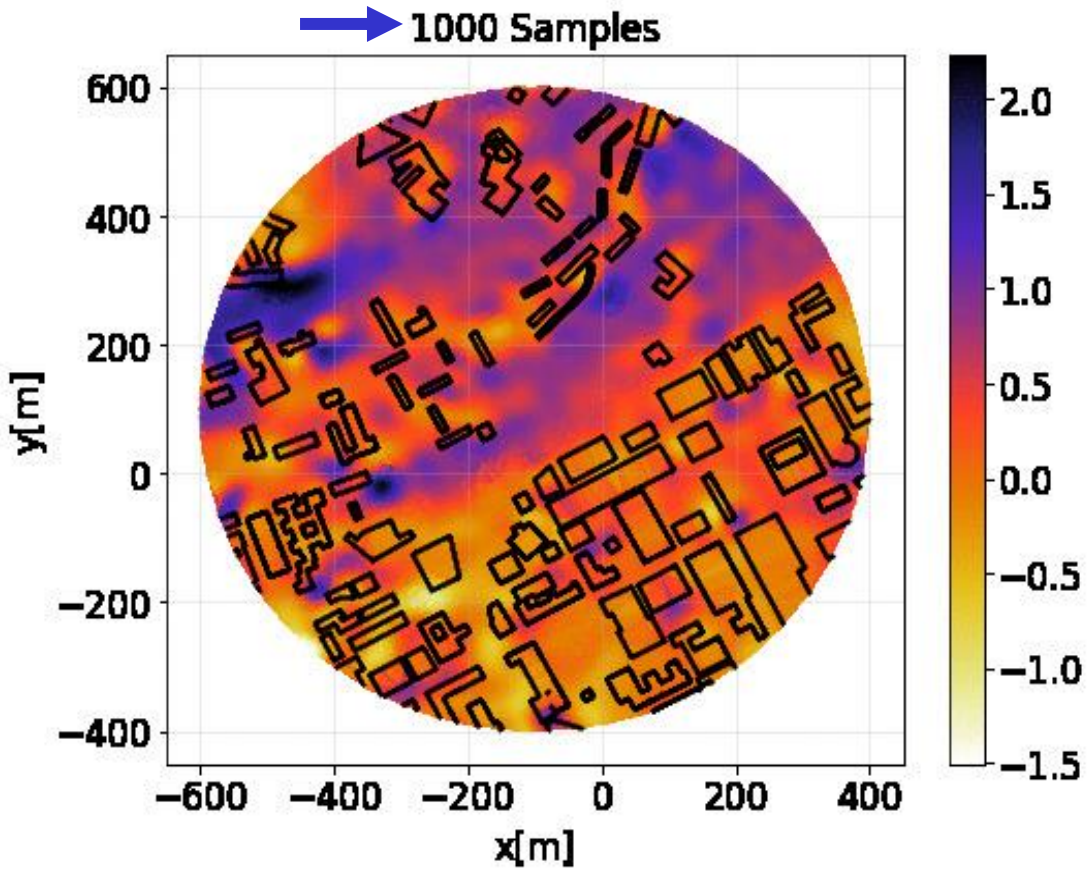

Surrogates for flow quantities over the space of x,y

- **Left**: Full dataset with 51k points in the x-y domain.
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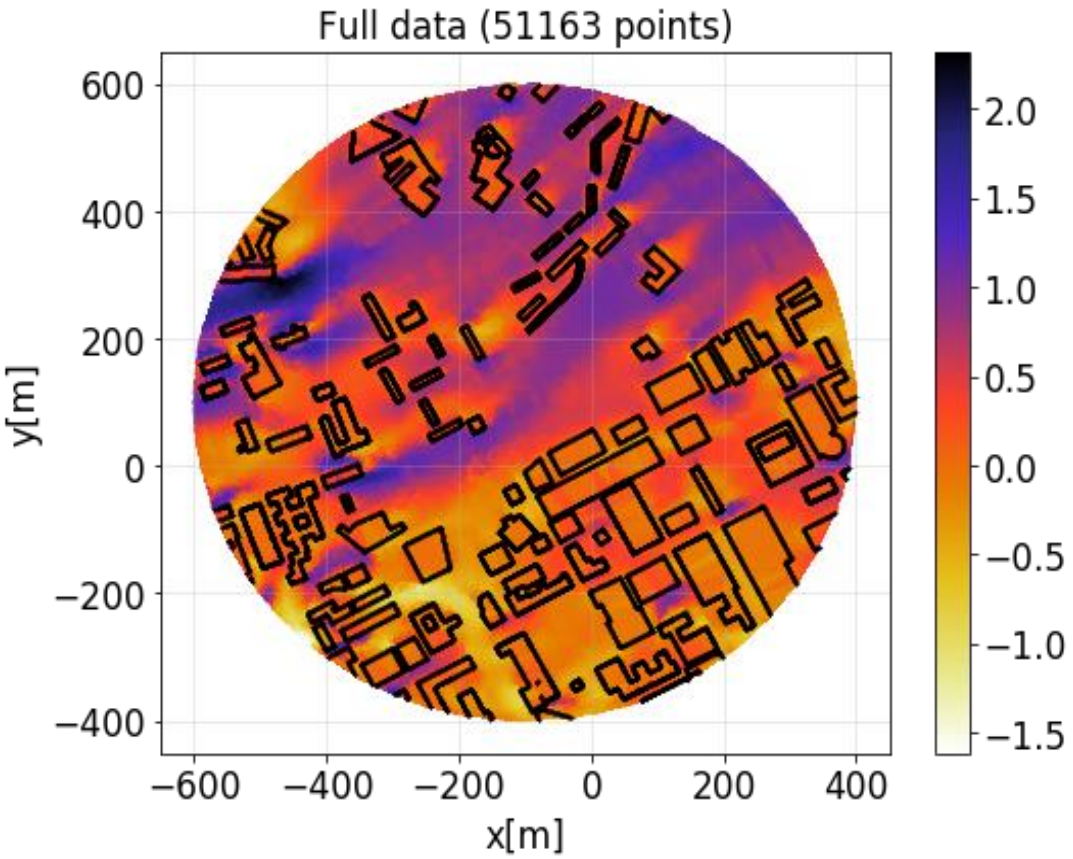
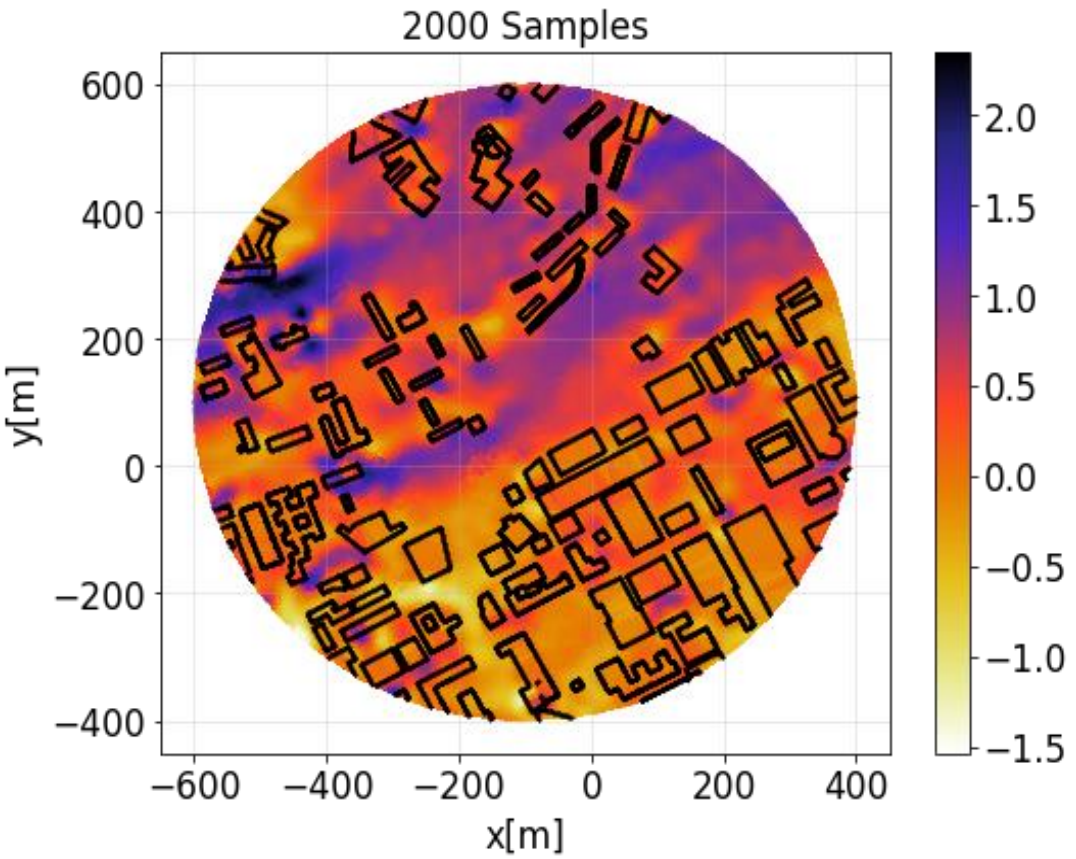
Final set of samples



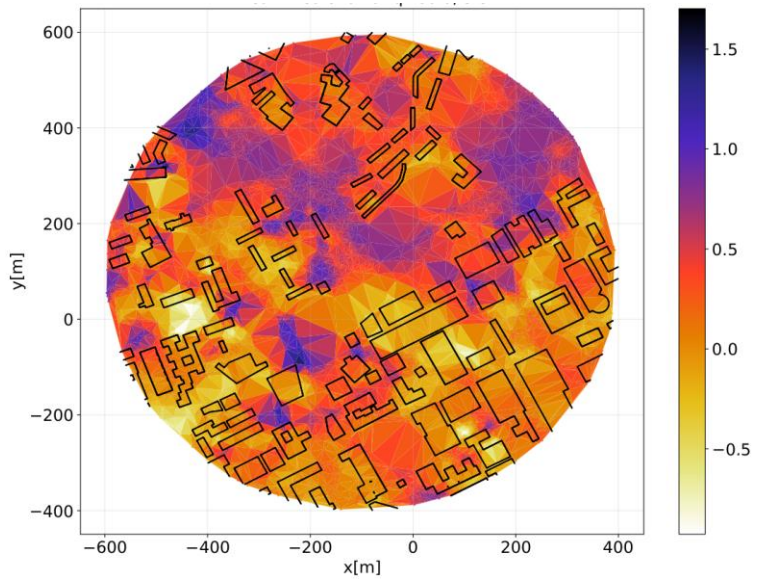


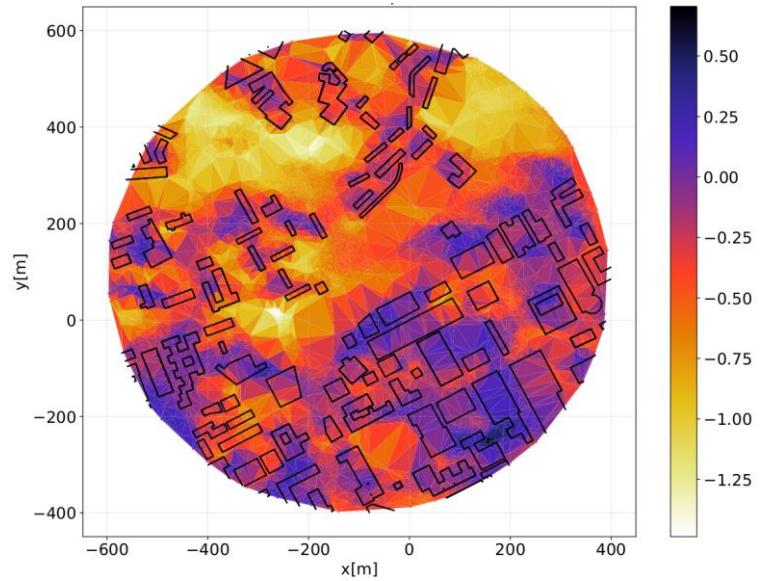
Prediction of the wind velocity at given windspeed and wind direction

60 deg & 3.3 m/s

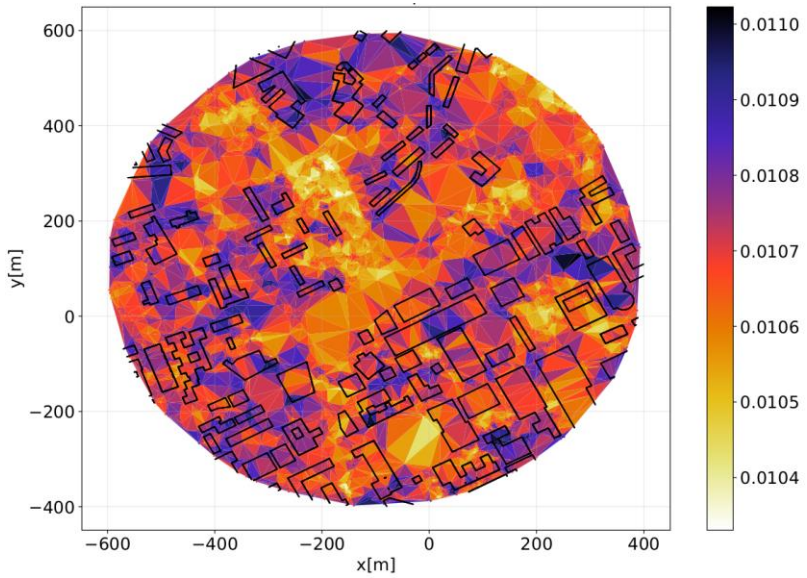
200 deg & 2.5 m/s

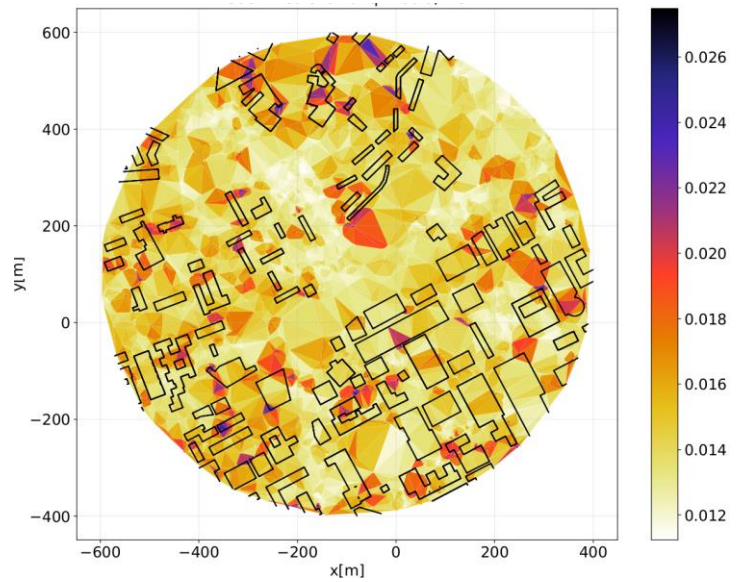
Mean Prediction





Sdev of Prediction



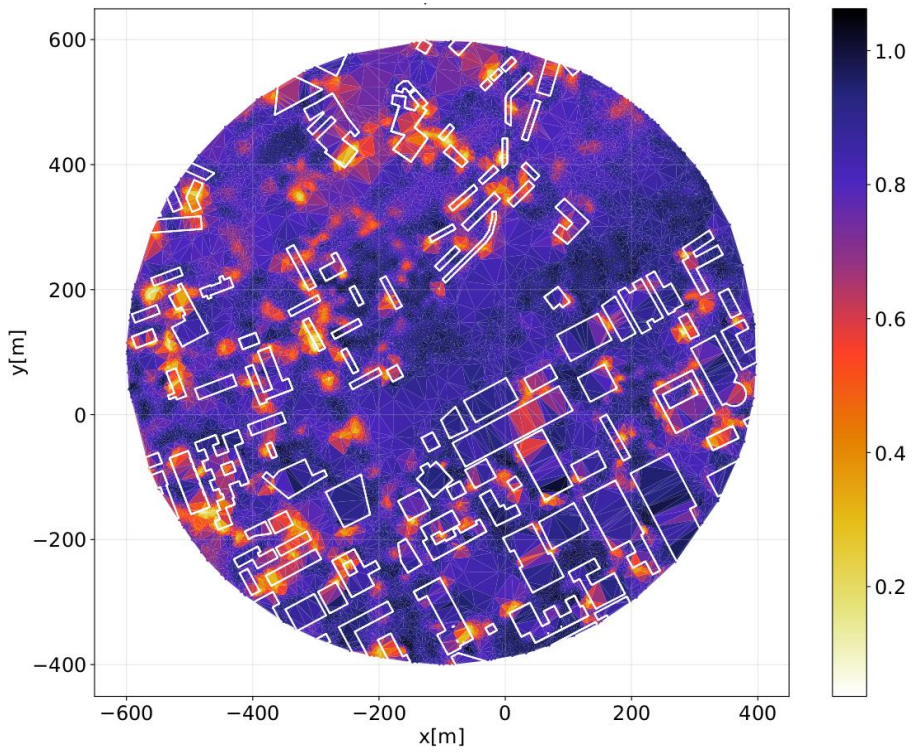


Effect of windspeed and wind direction

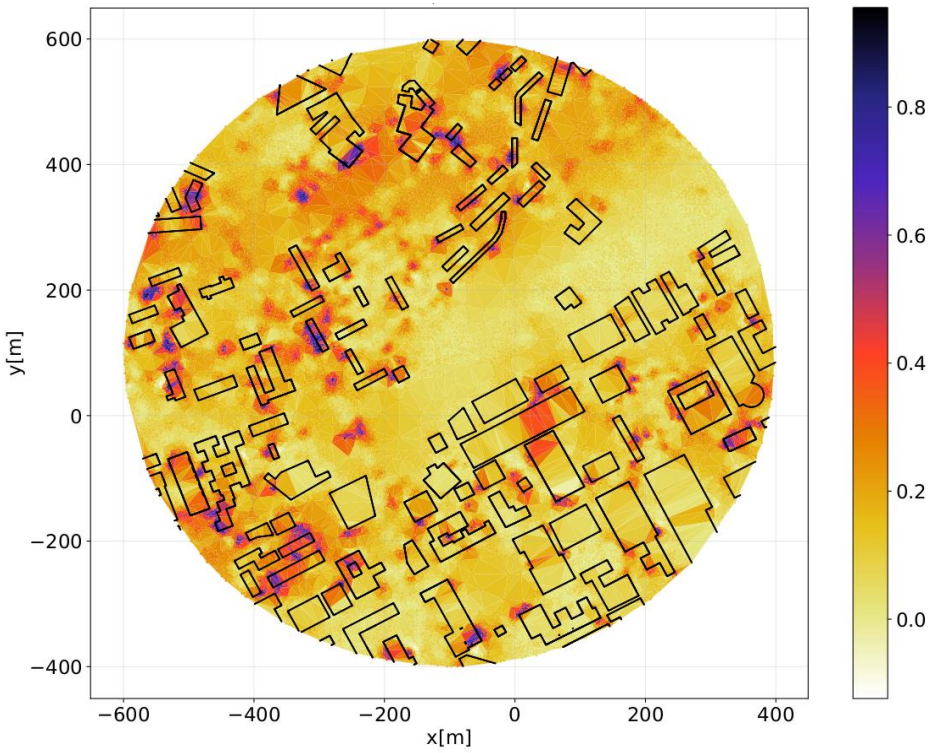
Global Sensitivity Analysis using ANOVA Technique (Sobol Sensitivity Indices)

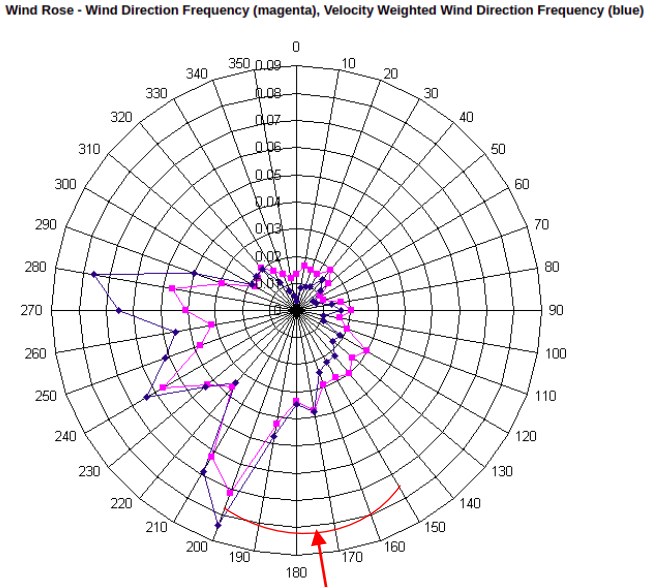
Main Sobol Indices with respect to,

Wind angle



Wind speed





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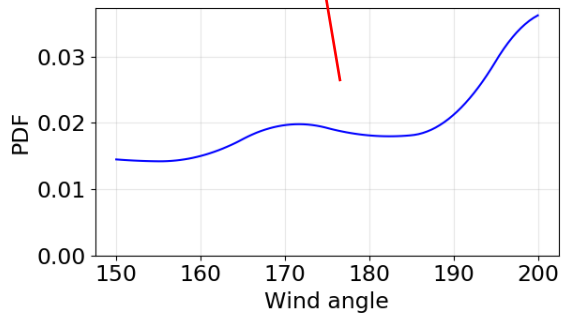
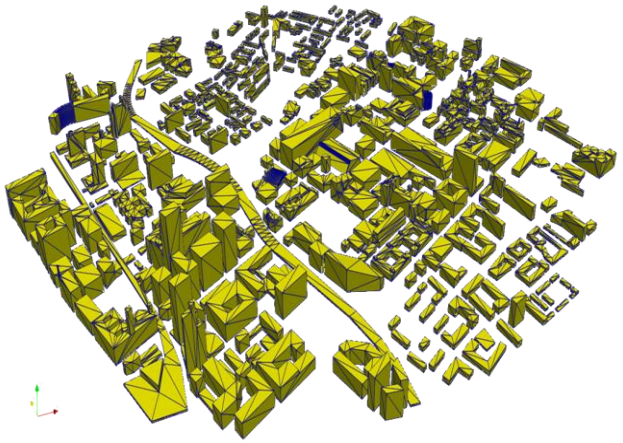


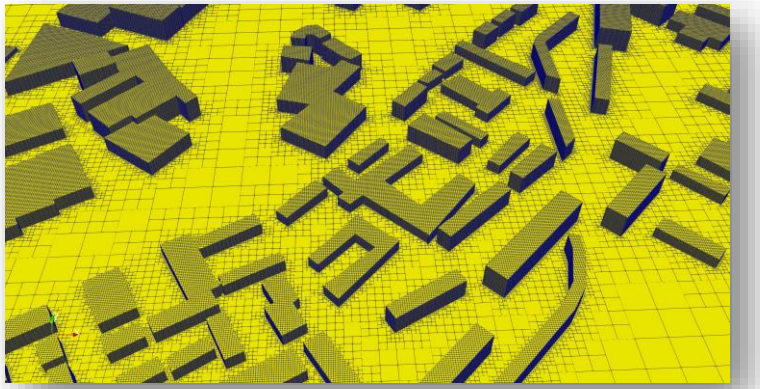
Wind speed ~U[3.2,3.5]

Some challenges in using RANS for urban physics

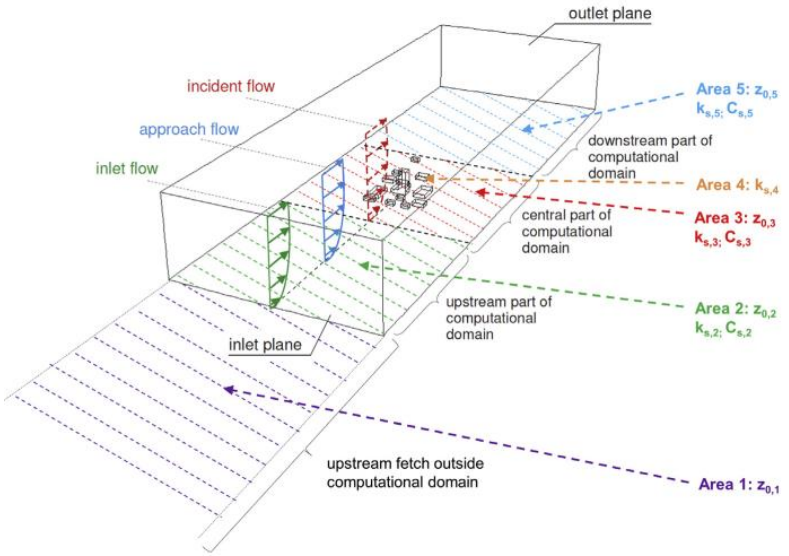
Challenge #1: Creating a high-quality computational grid

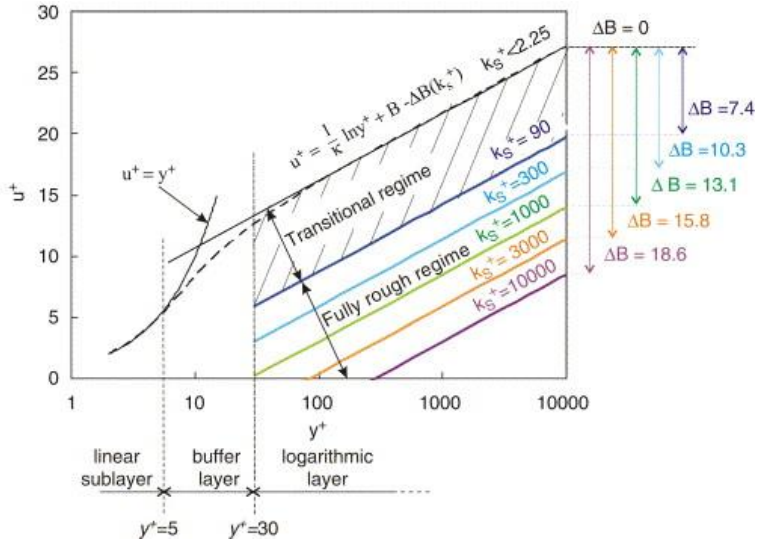
Challenge #2: Using higher-order discretization schemes



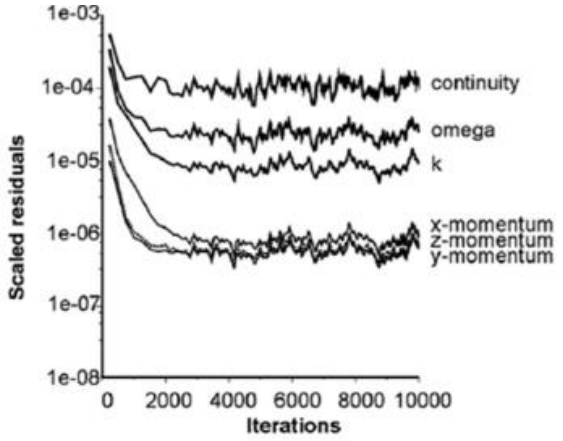


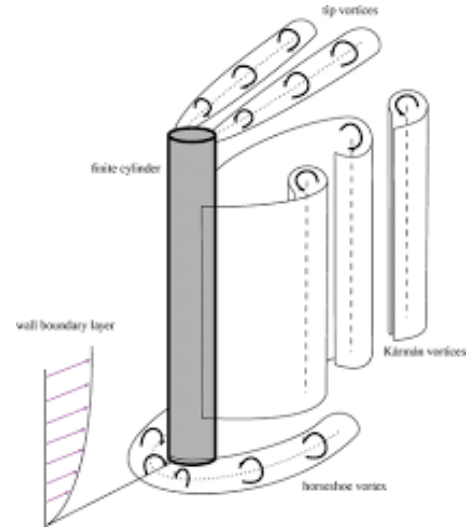
Challenge #3: Appropriate roughness parameters & wall functions





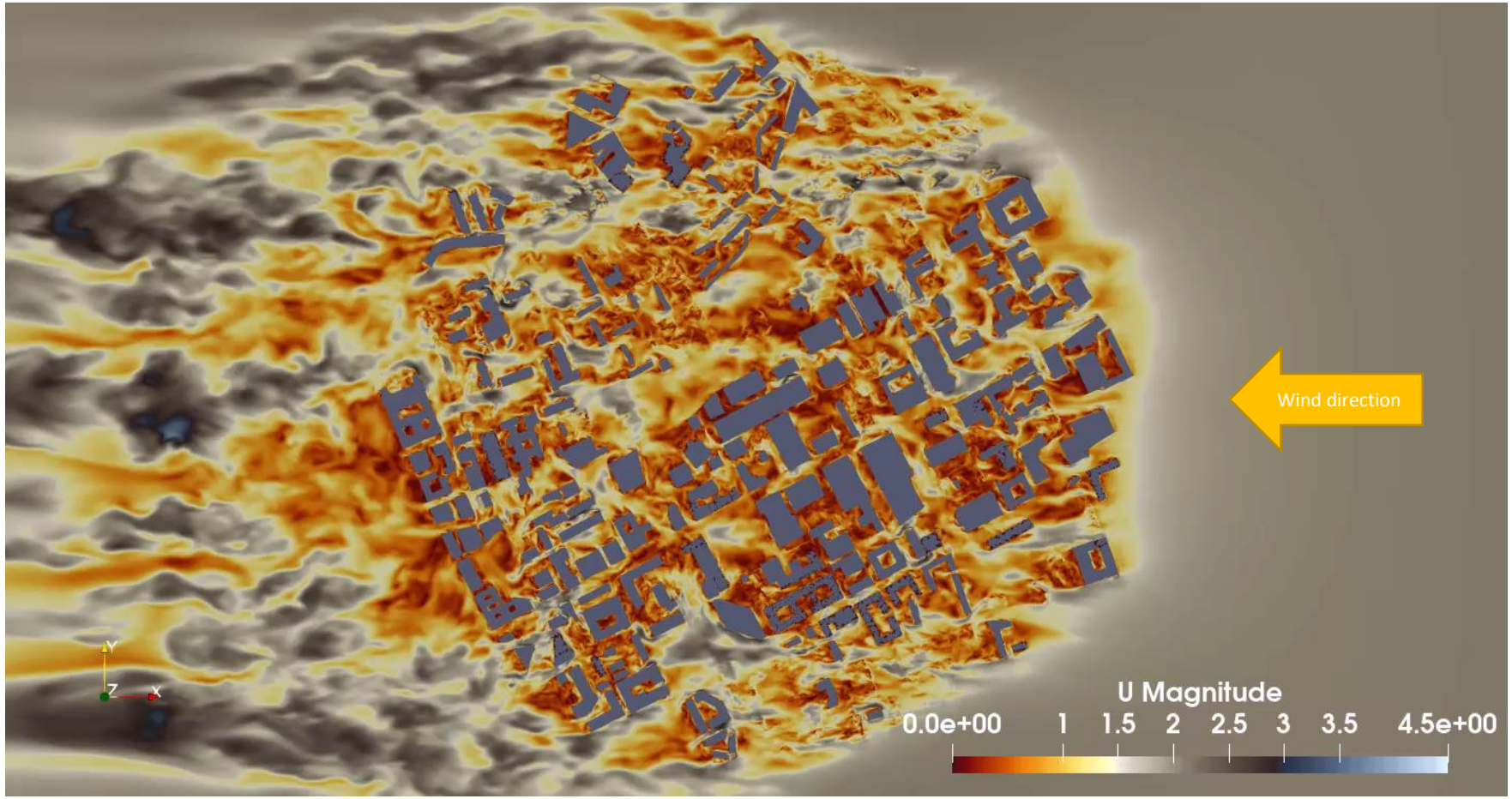
Challenge #4: Urban flow are intrinsically transient due to vortex shedding of buildings (bluff body)





Some challenges in UQ

- Turbulent flow simulations can be uncertain and are computationally expensive.
- We are developing a Multifidelity Modeling Approach based on RANS and LES data (*ongoing*).



Animation 1. Large eddy simulations of flow evolution

Summery

- 24 CFD cases are now available in our database which seems to be adequate for the start of the next step: UQ analysis
- Uncertain variables are: U_{ref} (3.0, 2.5 and 3.5)and wind directions (8 directions)
- UQ code was developed

In progress

- Increasing the quality of the grid (0.5 billion is now available)
- Investigating the effect of different wall functions
- Performing High fidelity LES and hybrid RANS/LES

Thank you

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