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Envisaging a world with greener cities

Managing Air for Green Inner Cities

Next generation numerical modelling tool for clean air environment

20, September 2018

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Numerical Modelling

fluidity

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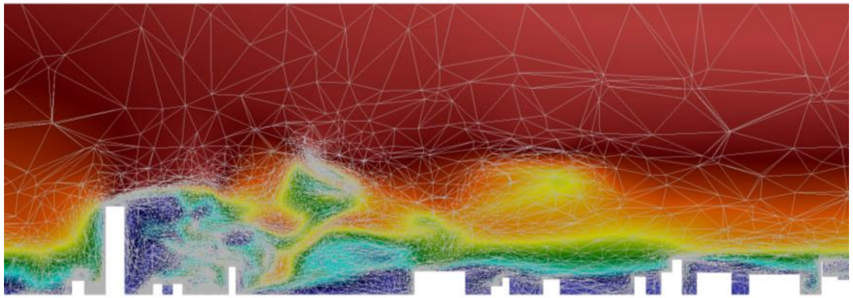
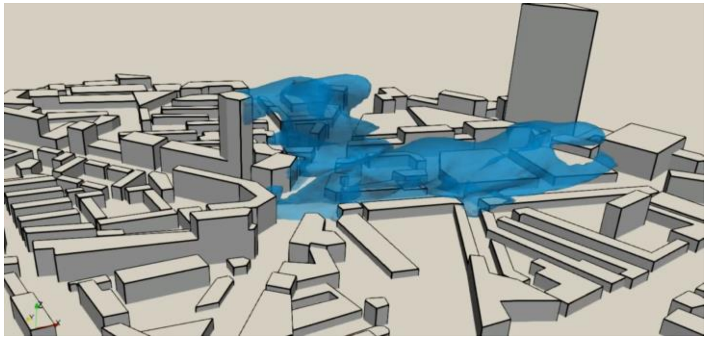
- Open-source CFD software for Multiphysics problems
- Finite-element method
- Unstructured and adaptive mesh
- Model for turbulence: Large Eddy Simulation (LES) approach
- Inlet velocity: synthetic eddy method
- User-friendly GUI
- Python interface to calculate diagnostic fields, to set prescribed fields, initial and boundary conditions





Next generation numerical tools for clean air environment

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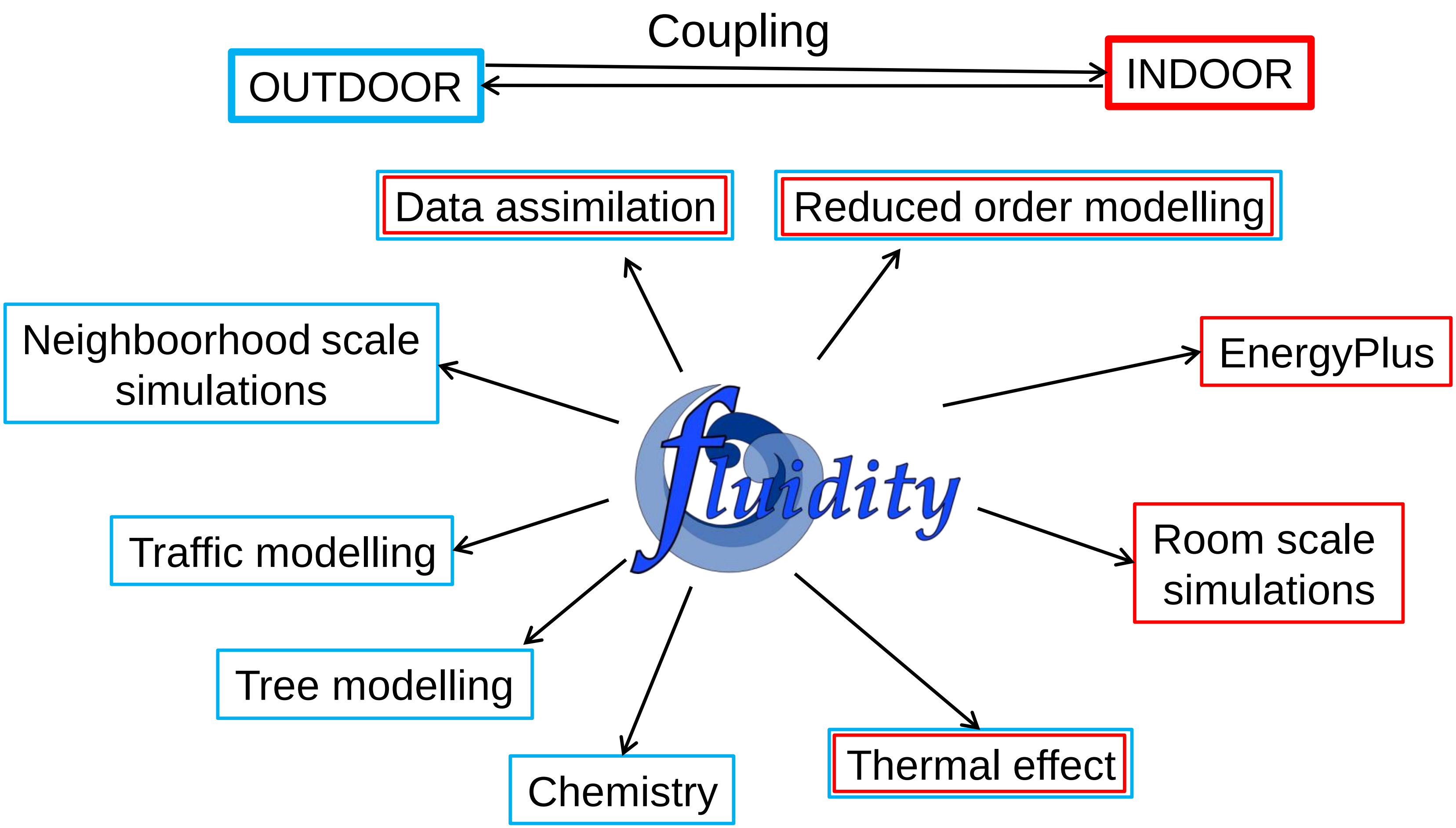

A list of numerical modelling tasks

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- Development and applications of the numerical model within *Fluidity*
  - Traffic modelling (Huw)
  - Chemical modelling (Huw – small scale, IAP/IUE – large scale)
  - Thermal modelling
  - Tree modelling
  - Validation of the model
- Towards real-time operational predictive numerical tool
  - Data assimilation
  - Reduced order modelling
- Collaboration work from our research partners (large scale atmospheric and air pollution modelling)

Part 1 – Numerical model development, Validation and applications

Thermal modelling

Thermal modelling

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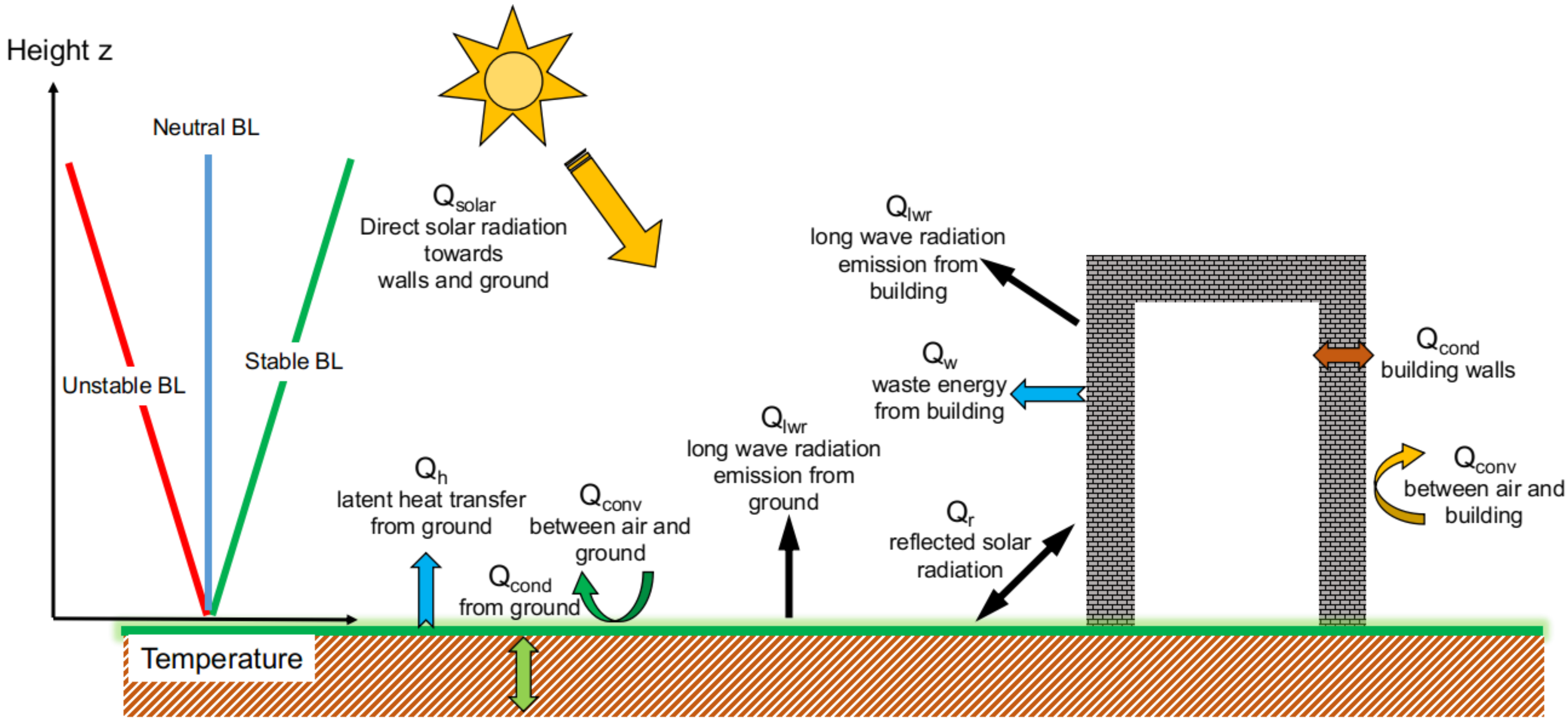
- Main factors influencing the urban microclimate



Thermal modelling

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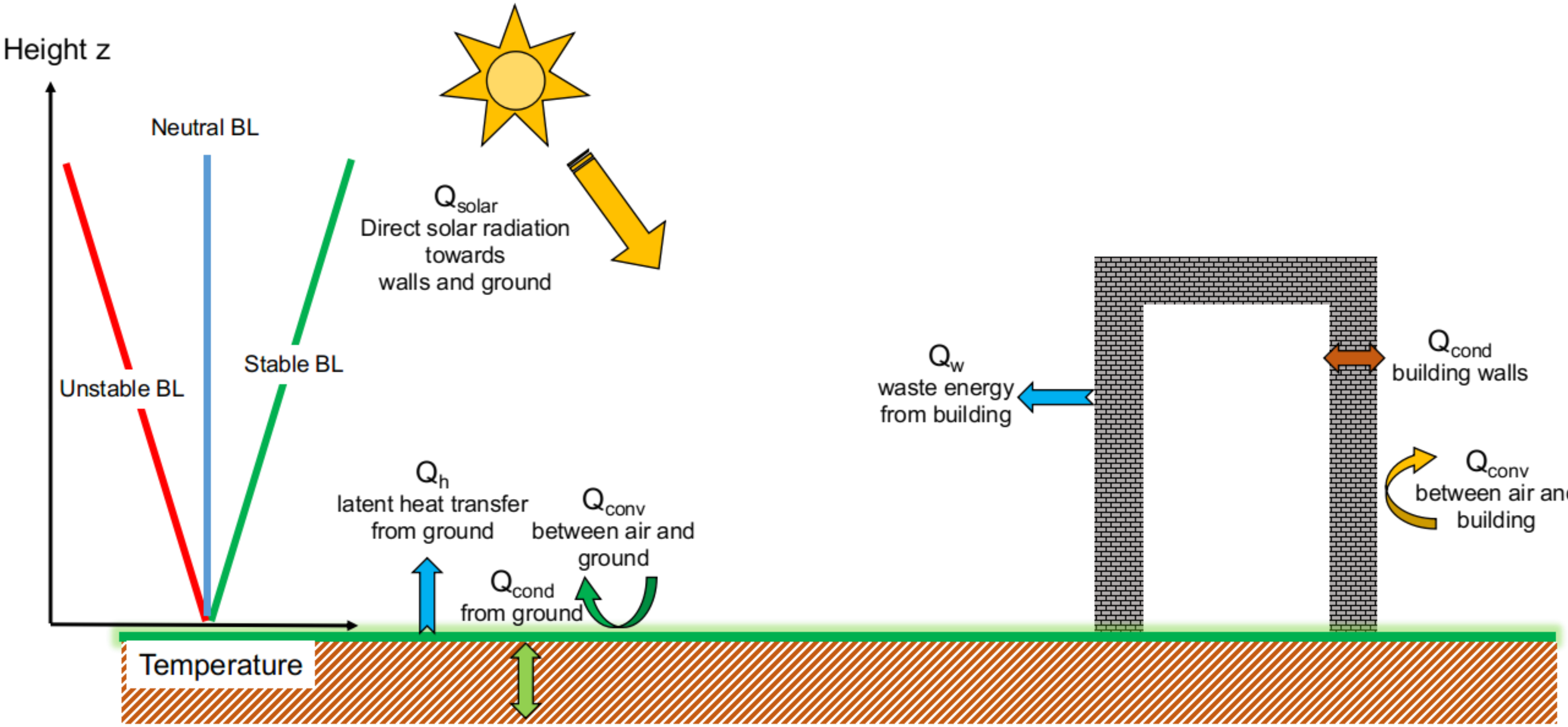
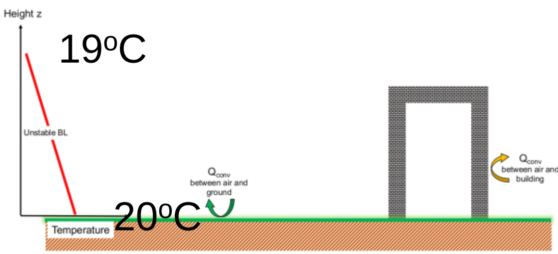
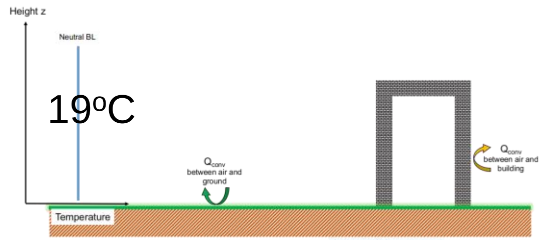
- Main factor influencing the urban microclimate: implemented or under testing

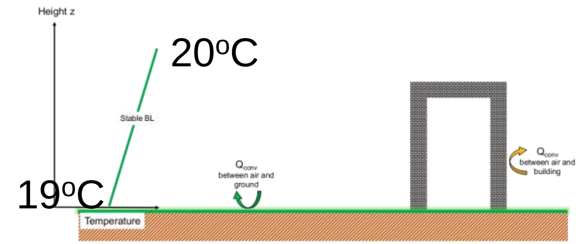


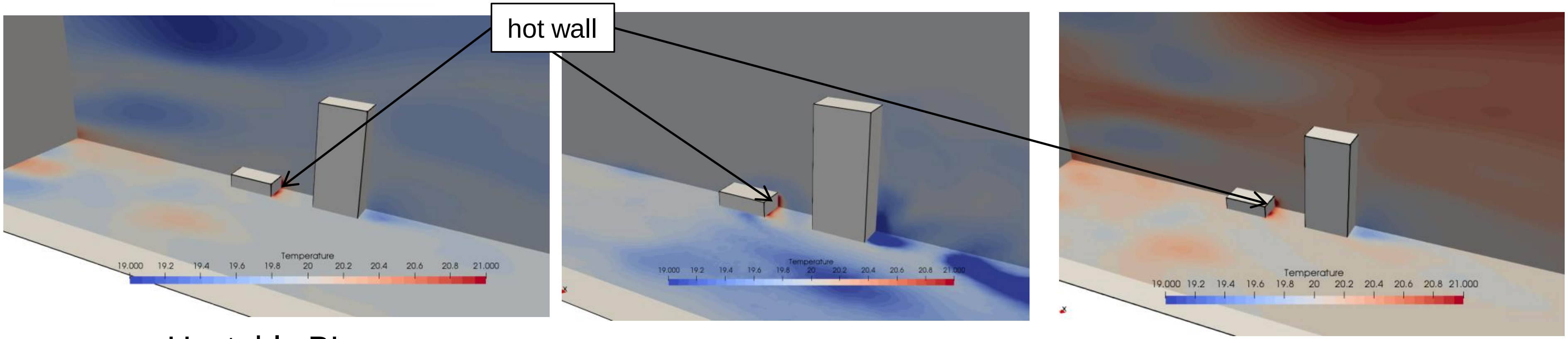
Thermal modelling

Turbulent inlet temperature profiles









Unstable BL

Neutral BL

Stable BL

T_{init} = 20ºC

One "hotter" wall at T=25ºC; T=20ºC otherwise.

Convective coefficients as a function of:

- the local average temperature between the ground/wall and the air.
- the local velocity near the ground/wall.

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Thermal modelling

Turbulent inlet temperature profiles

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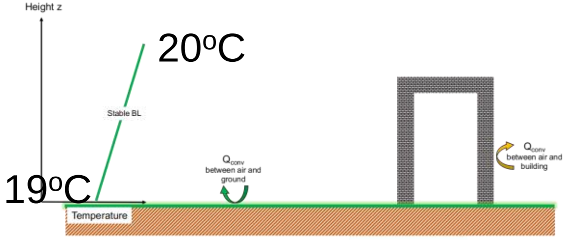
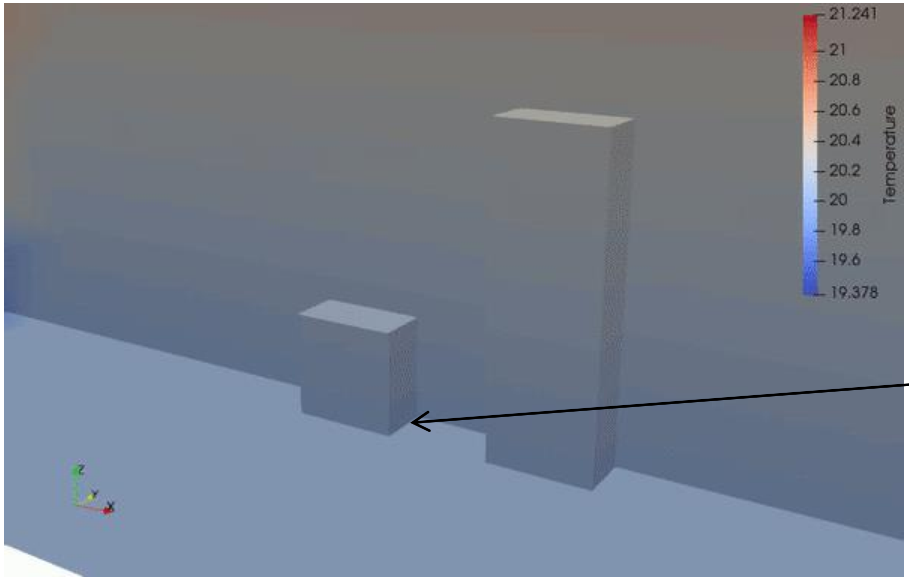
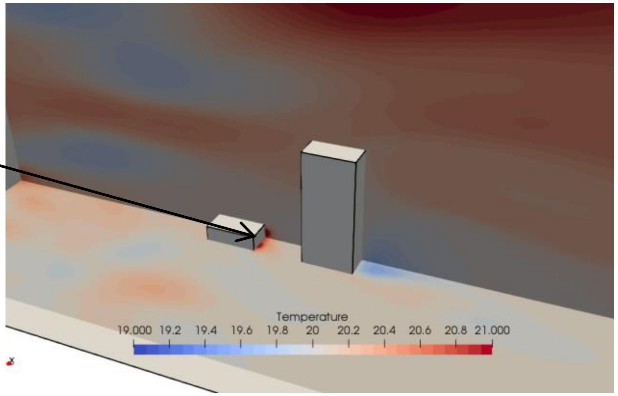




Stable BL



Stable BL

T_{init} = 20ºC

One "hotter" wall at T=25ºC; T=20ºC otherwise.

Convective coefficients as a function of:

- the local average temperature between the ground/wall and the air.
- the local velocity near the ground/wall.

Thermal modelling

Ground and wall conduction

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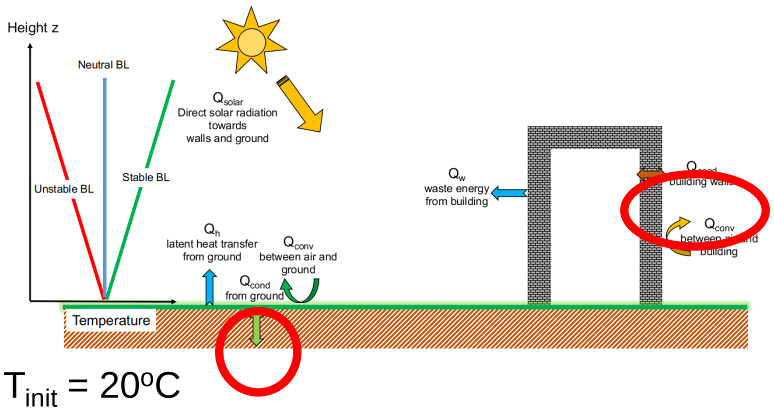
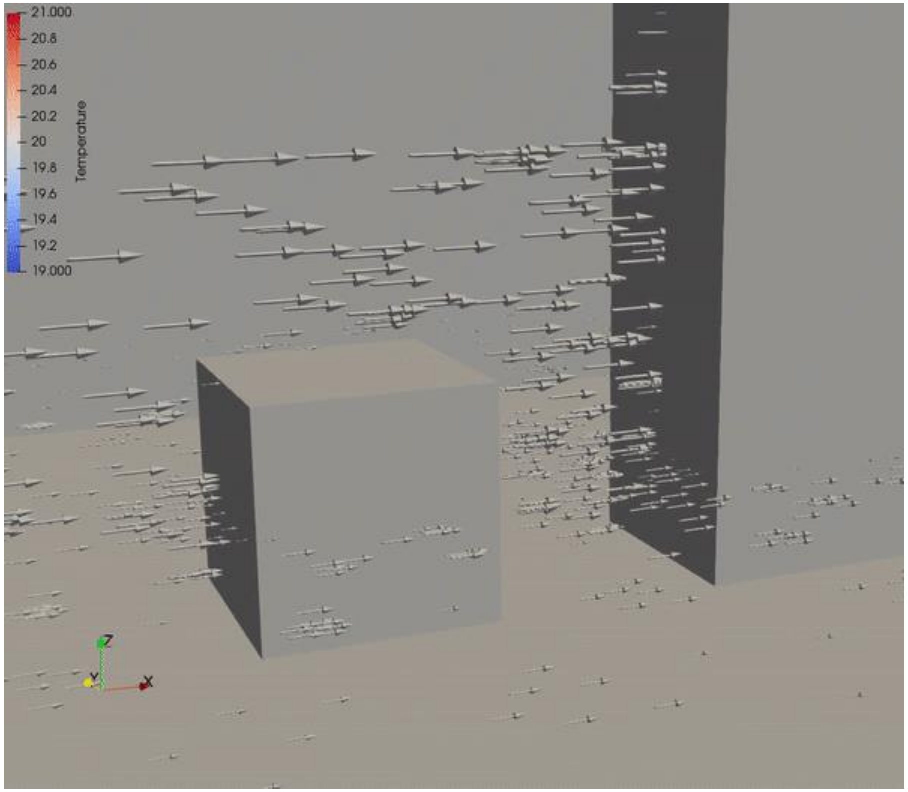


- T_{init} = 20ºC
- Constant inlet temperature = 20ºC

- Convective coefficients as a function of:
  - the local average temperature between the ground/wall and the air.
  - the local velocity near the ground/wall.

- One layer ground: T=10ºC at 10m depth.
- One layer wall: T=26ºC with wall thickness equal to 390mm.

- LES timestep and timestep for heat transfer in the ground and walls can be decoupled if desired.



Shadow zones

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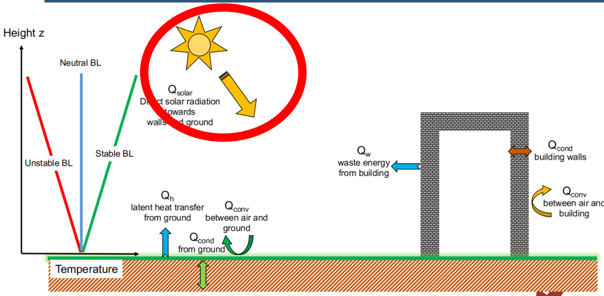
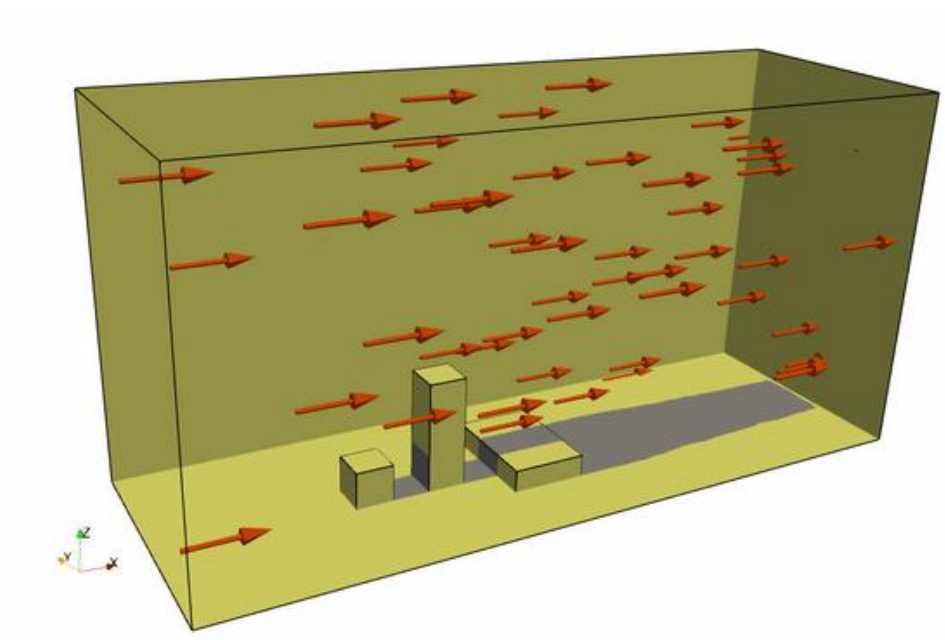
- Direct sunlight: will be used in radiation modelling





Test case area

Direction of the sun

LSBU area

Shadow zones

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Urban Terreno to generate the 3D mesh

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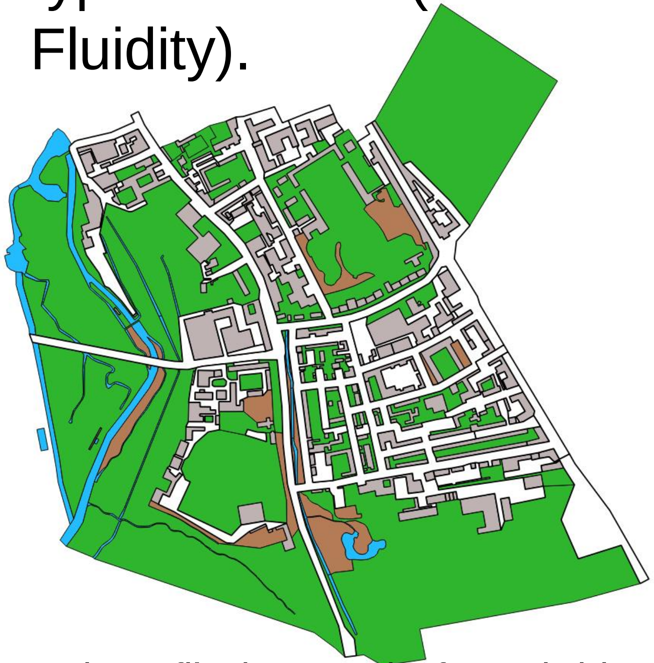
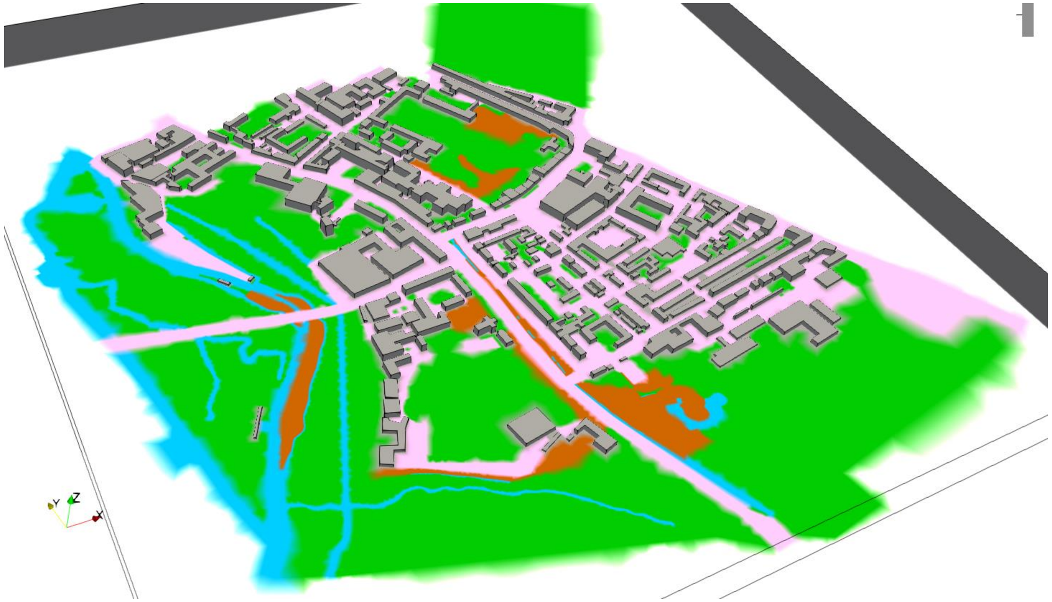
- Urban Terreno can now AUTOMATICALLY differentiate different types of lands (needed to assign proper boundary conditions in Fluidity).



Shapefile (2D map) of Cambridge



3D mesh generated by Urban Terreno

Buildings | Green Spaces | Wood Spaces | Blue Spaces | Roads

Comparison with wind tunnel data

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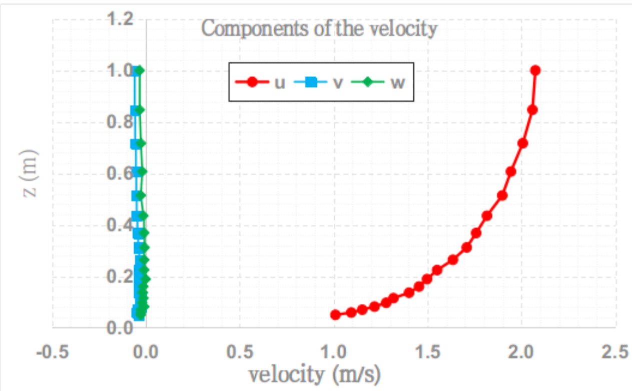
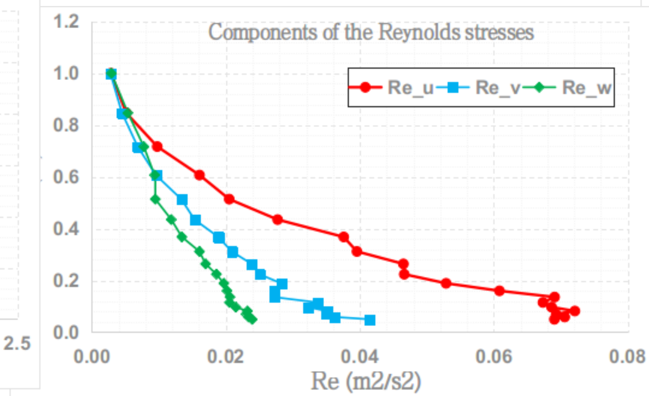
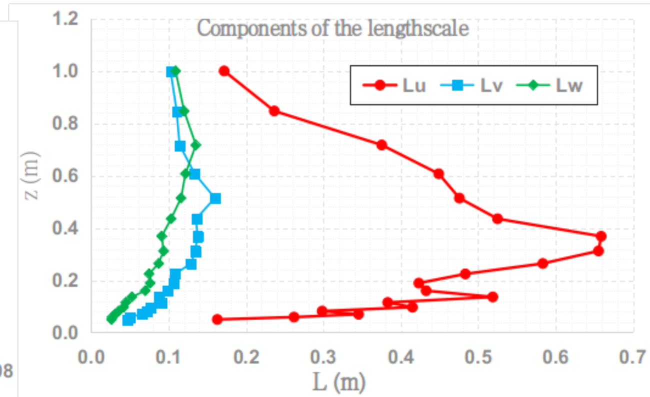
- Turbulent inlet boundary condition



Mean velocities



Reynolds stresses



Lengthscale

- Five wind directions.
- Comparison of the **mean velocity components** (u, v and w), the **Reynolds stresses** (u'u', v'v' and w'w') and the **pollutant concentration** (C) for horizontal and vertical profiles in several location in the domain.

Comparison with wind tunnel

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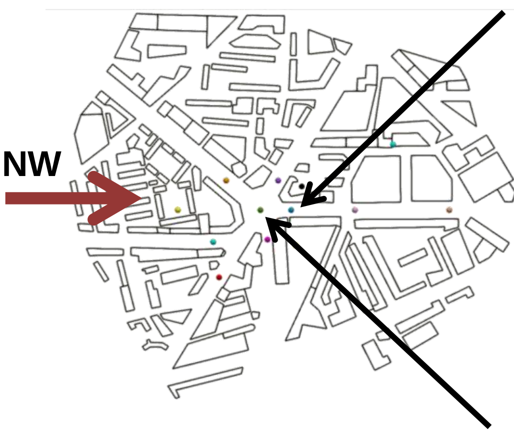
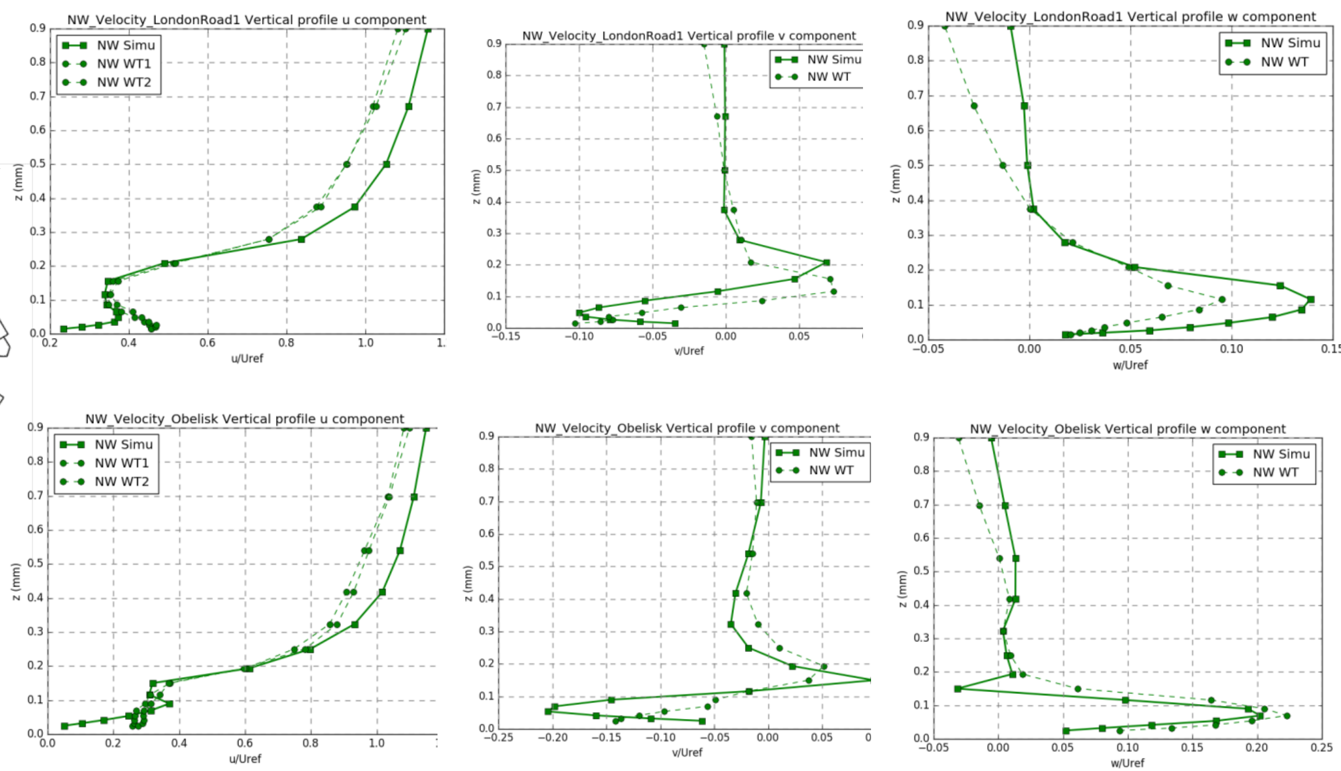
- Mean velocities: vertical profiles



u v w



Comparison with wind tunnel

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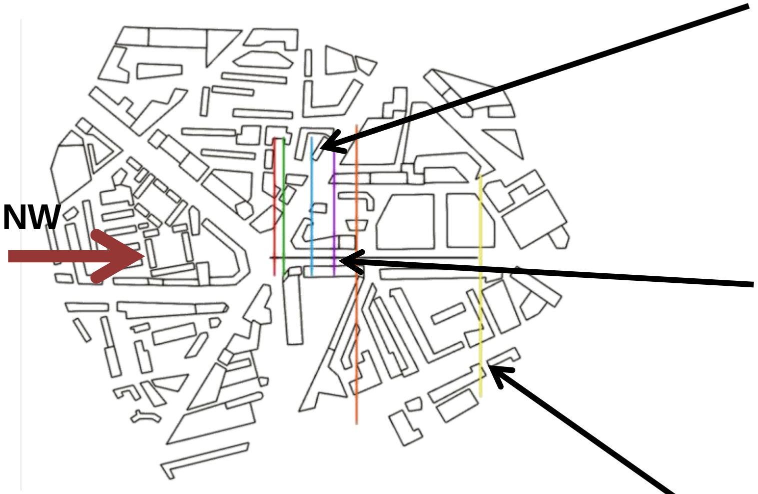
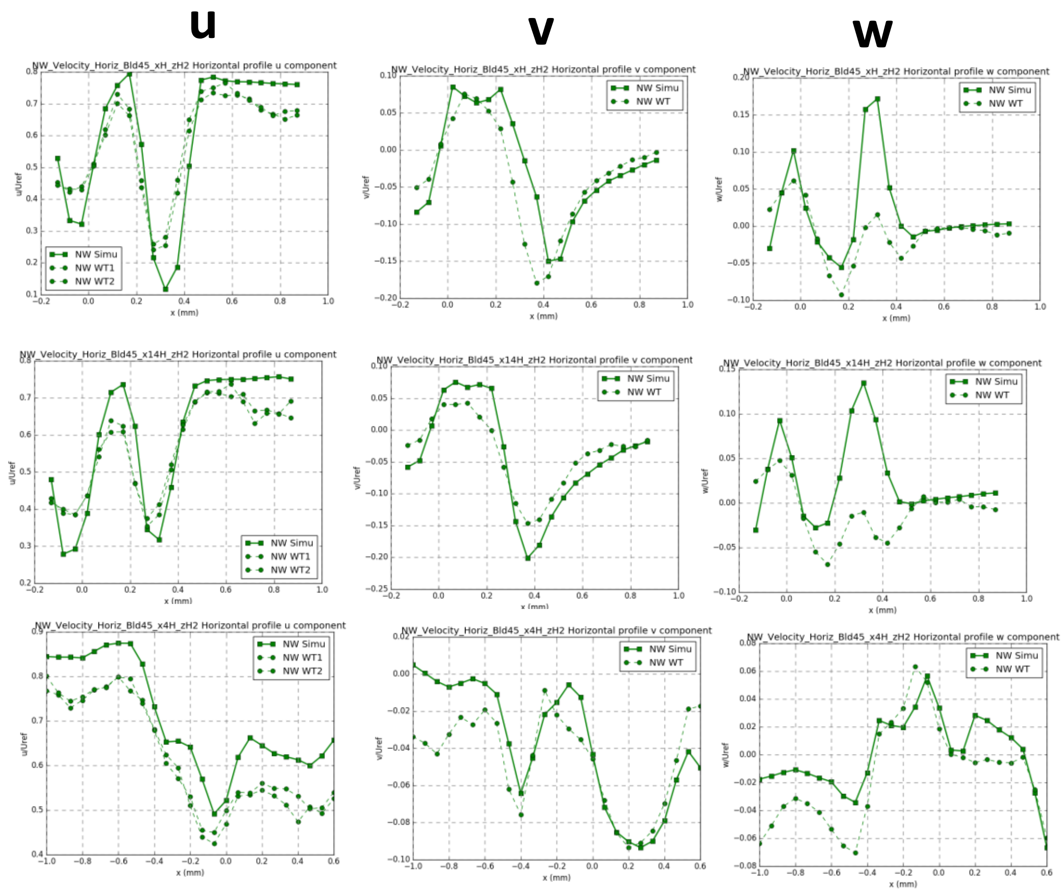
- Mean velocities: horizontal profiles





Comparison with wind tunnel

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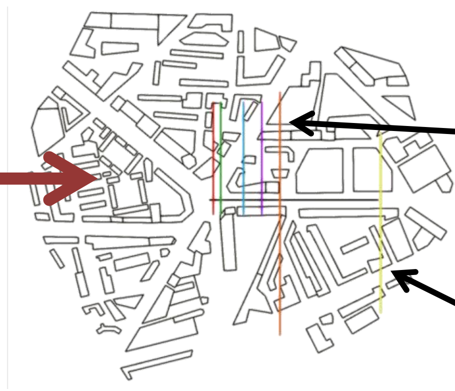
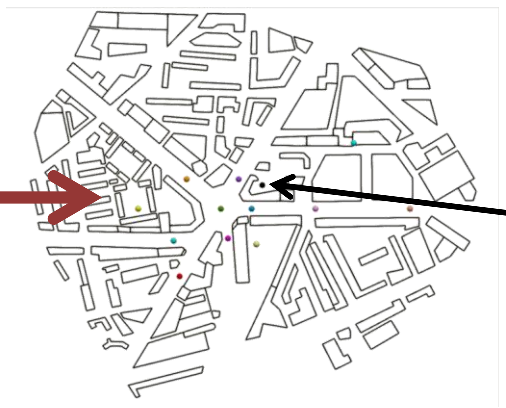
- Reynolds stresses

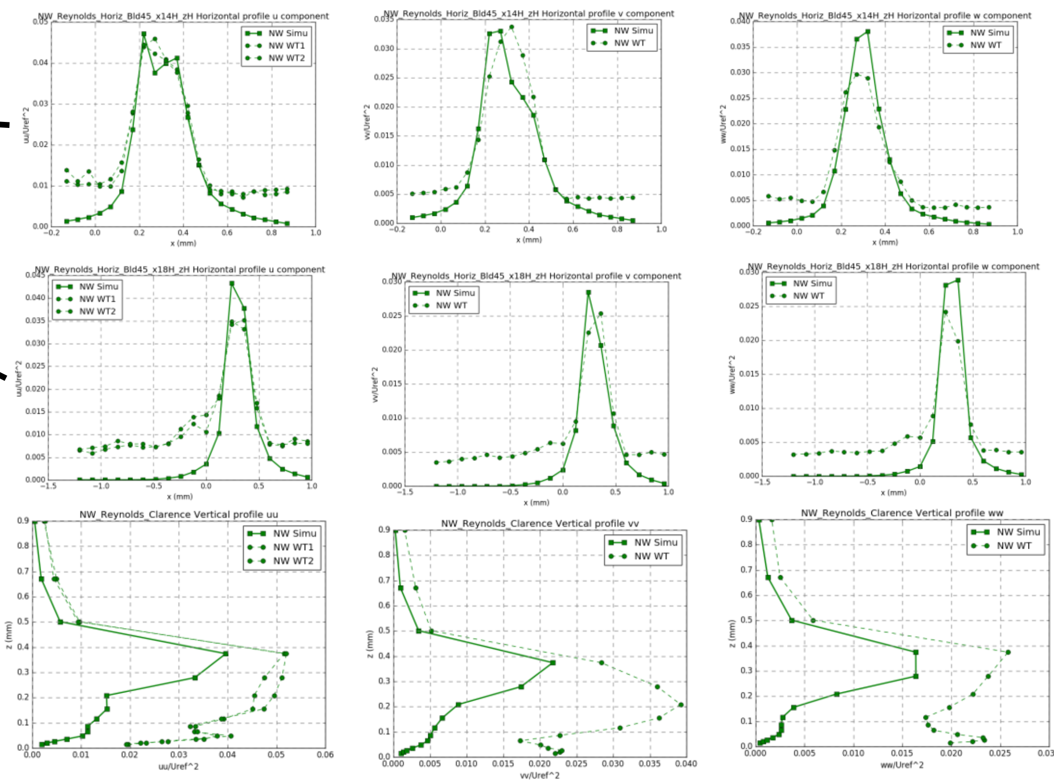
u'u' v'v' w'w'

NW



NW





Comparison with wind tunnel

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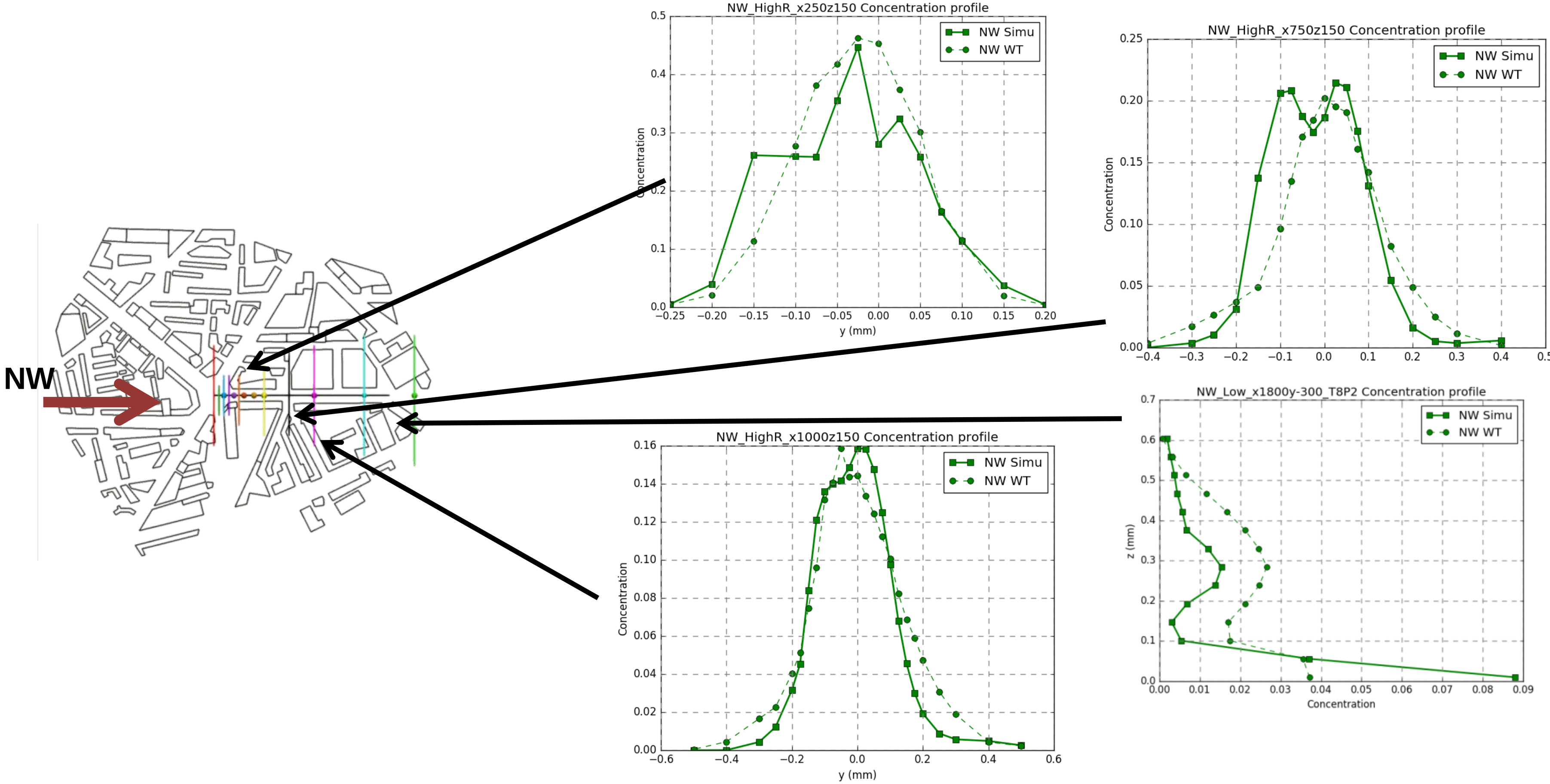
- Concentration



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Part 2a – Towards operational real time predictive modelling

Data Assimilation

Data Assimilation (DA)

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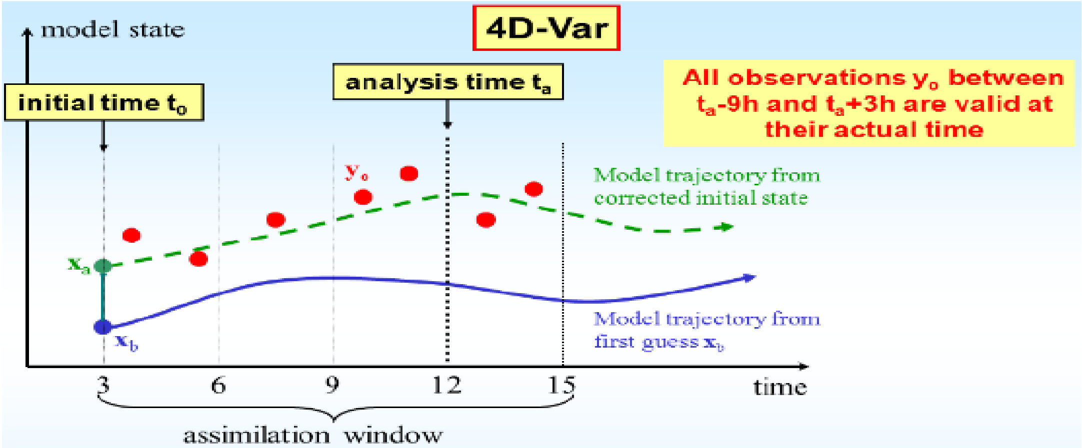
DA methods

- Optimal interpolation;
- Nudging;
- 3D-Var;
- 4D-Var (adjoint);
- Ensemble KF

Motivation for DA

- Improve accuracy of results;
- Uncertainty sensitivity analysis;
- Optimisation of uncertainties in models;
- Goal-based error measurement and mesh adaptivity;
- Design optimisation;
- Adaptive observation (optimisation of sensor location).



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Optimal Space for Variational Data Assimilation

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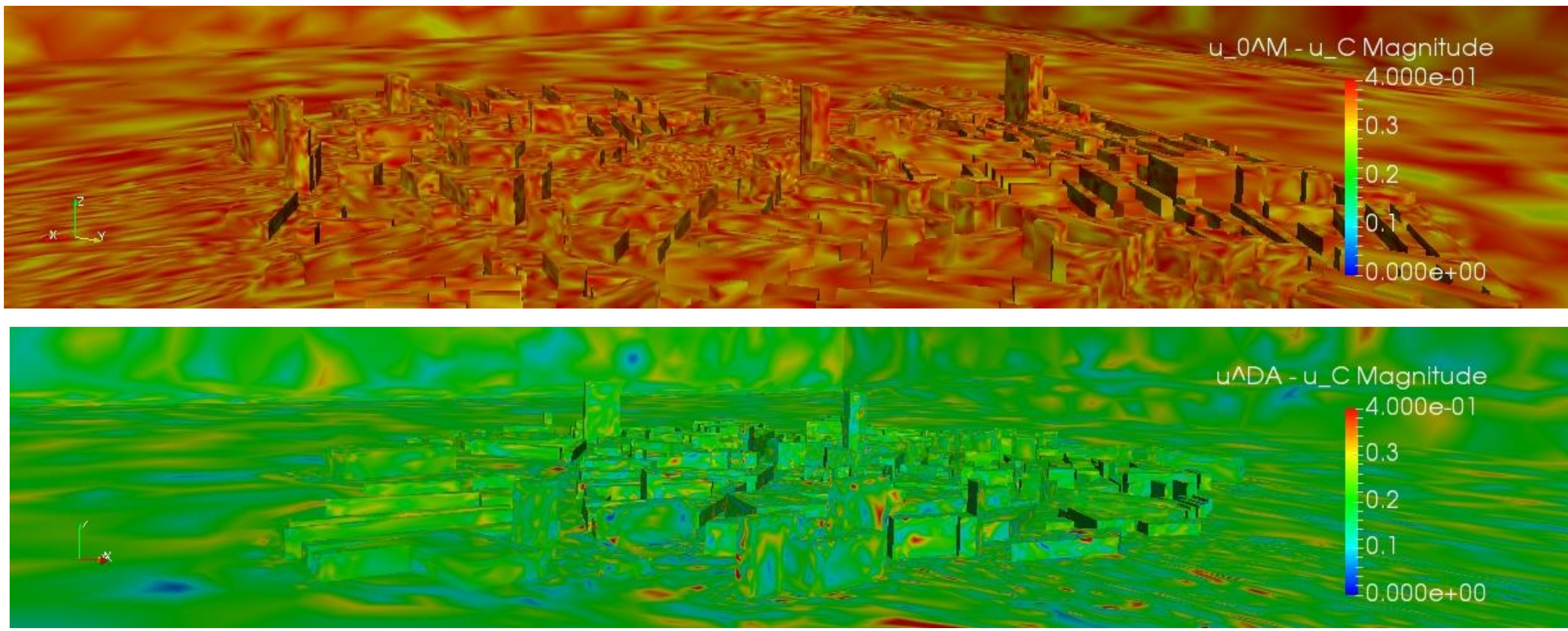
- The problem is solved in a reduced optimal space
  - The solution computed in the optimal space minimizes the errors.
  - These results were validated using test cases (LSBU).

Before DA

After DA



Error magnitude for the velocity field

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Optimal Space for Variational Data Assimilation

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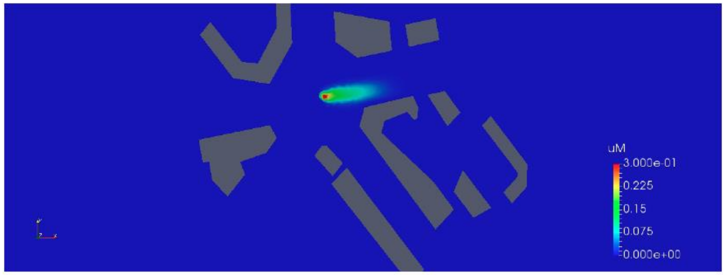
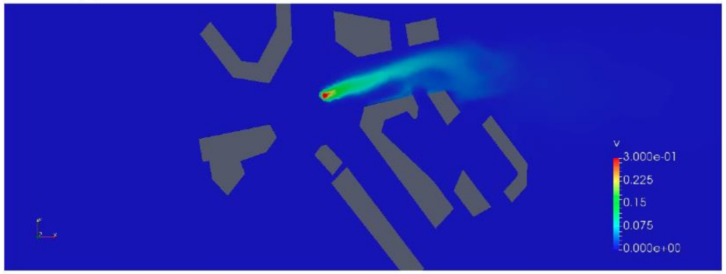
Numerical solution



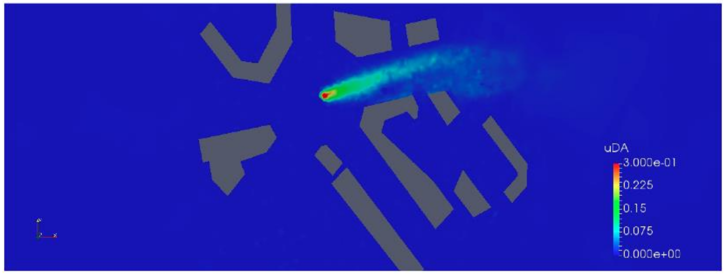
(a) Values of u_0: predicted pollutant concentration field

Observational data



(b) Values of v: observed pollutant concentration field

Solution after DA



(c) Values of u^{DA}: assimilated pollutant concentration field

Pollutant concentration

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Domain Decomposition based Variational Data Assimilation (DD-VarDA)

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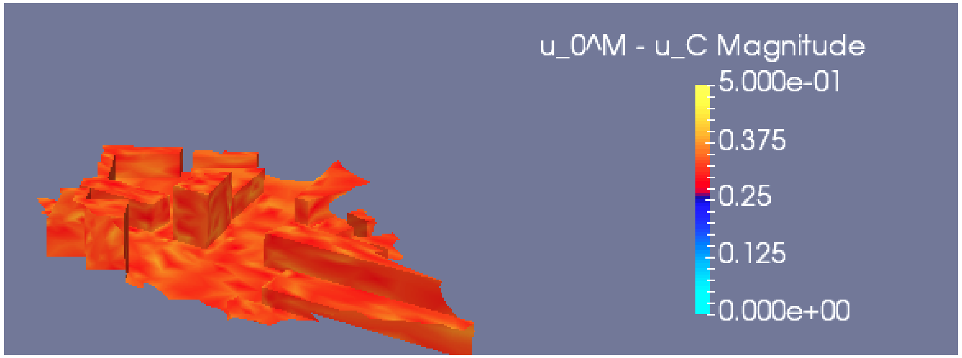
- The problem is solved on a decomposed domain
  - **Accuracy:** The solution computed with the solutions on each subdomains is the same than the solution computed on the whole domain without any decomposition.
  - **Efficiency:** The execution time is reduced even if the DD-VarDA code runs on 1 processor.
  - **Validation:** These results are validated using test cases (LSBU).

Sequential **execution time**: **6149.59** sec

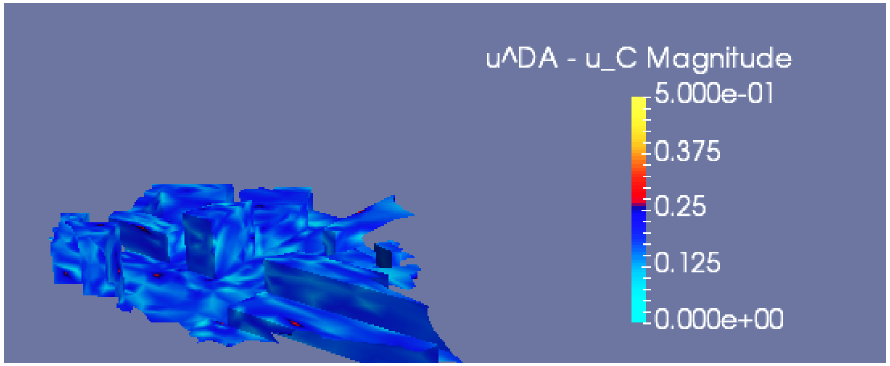
Using **only 1 processor**

Time ÷ 2.4

Execution time (10 subdomains): **2525.72** sec



Error before DA



Error after DA

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Towards real time predictions by combining DA and NIROM

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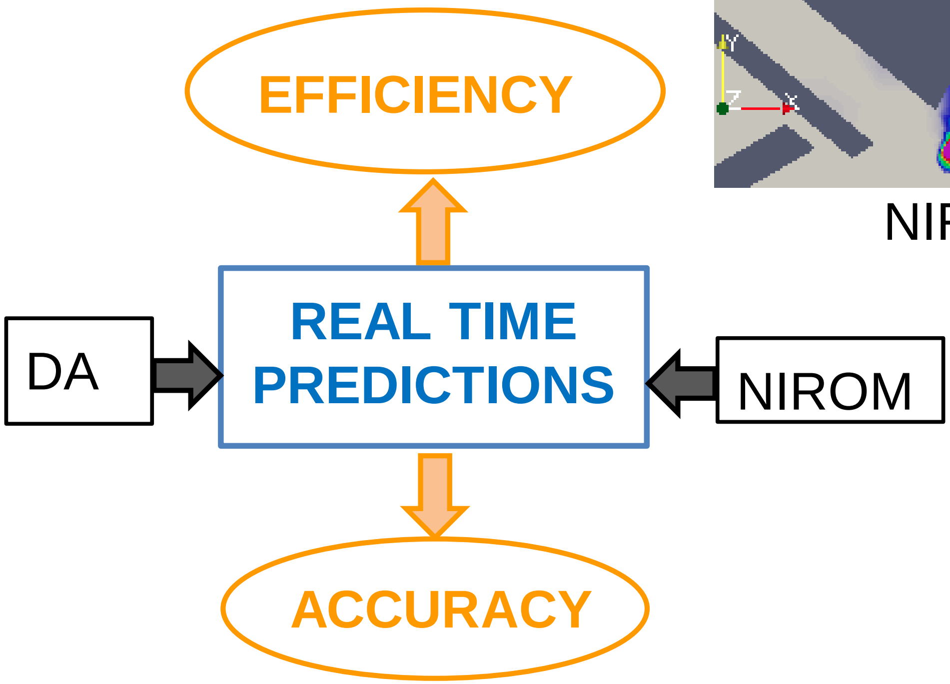
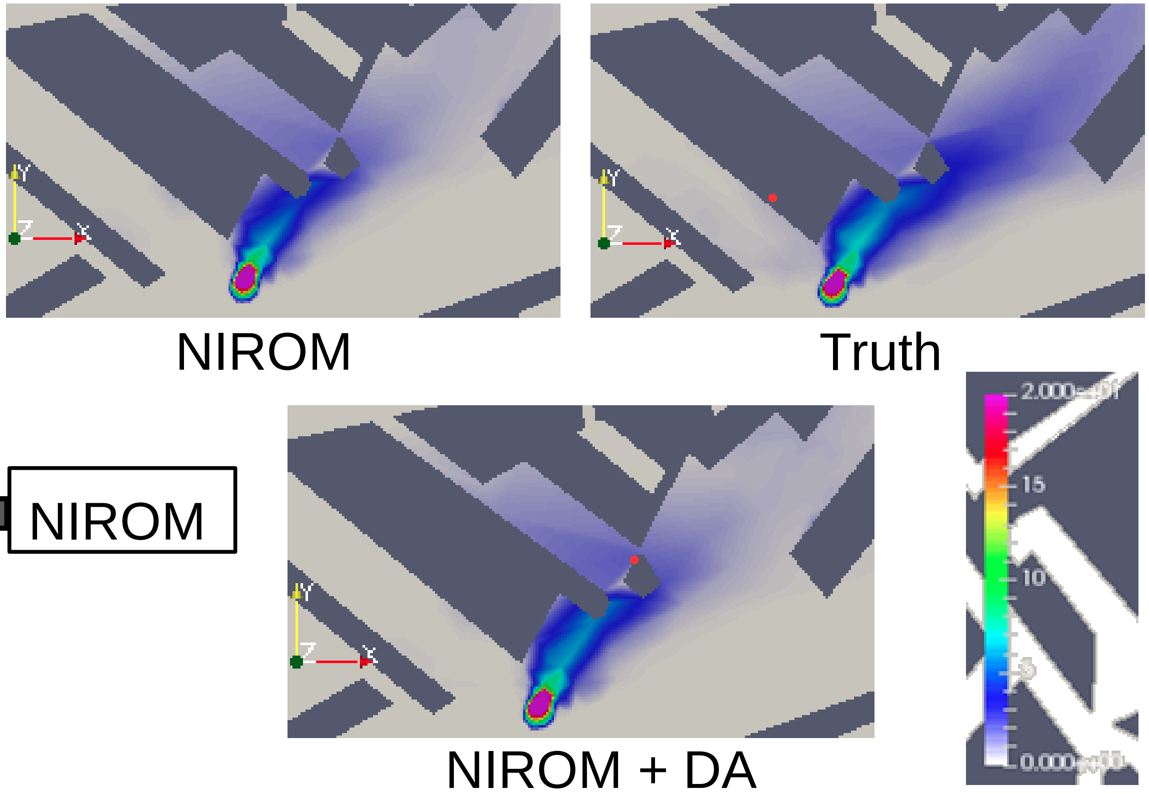
- NIROM and VarDA are combined in a prediction-correction cycle.





Future works

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- **Hybrid Data Assimilation**: Combining Variational Data Assimilation with Ensemble Kalman Filter.

- **Deep Data Assimilation**: Combining Data Assimilation with Deep Learning

- **Domain Decomposition Data Assimilation** with **Domain Decomposition Reduce Order Modelling**

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Part 2b – Towards operational real time predictive modelling

Reduced order modelling

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Domain decomposition non-intrusive reduced order modelling (DD-NIROM)

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Objectives

DD-NIROM is developed for large-scale (km scale) problems (entire city) with many degrees of freedom. By using the DD-NIROM:

- ❖ The details of local flow features (eddies, for example) can be captured, thus improving the **accuracy** of results;
- ❖ The computational **efficiency** can be further improved, especially in combination with parallel computing techniques.

Domain decomposition non-intrusive reduced order modelling (DD-NIROM)

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Methodologies

- ❖ NIROM by using Proper Orthogonal Decomposition (POD) and machine learning methods.
- ❖ The sub-domains are chosen through a weighting constraint which aims to:
  - achieve an equal accuracy in each sub-domain
  - minimise the dynamic activity between sub-domains (each subdomain is almost isolated – little communication between the sub-domains)

Domain decomposition non-intrusive reduced order modelling (DD-NIROM)

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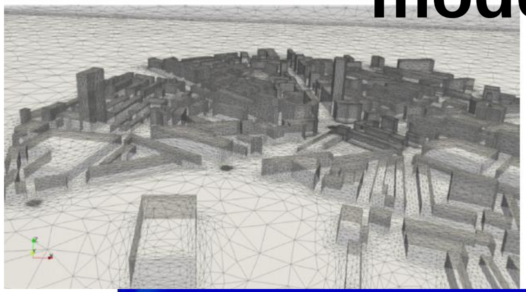
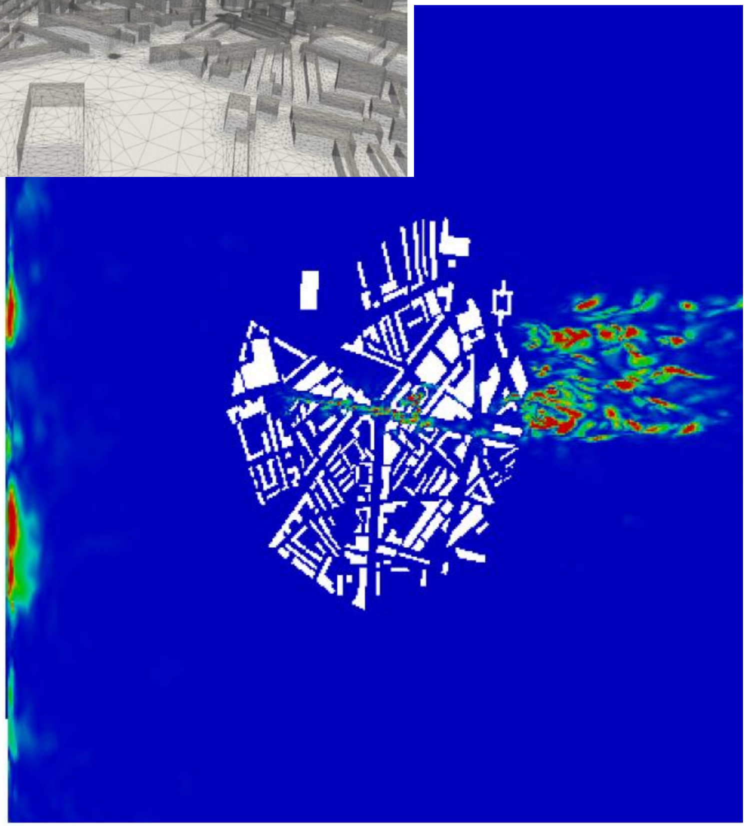
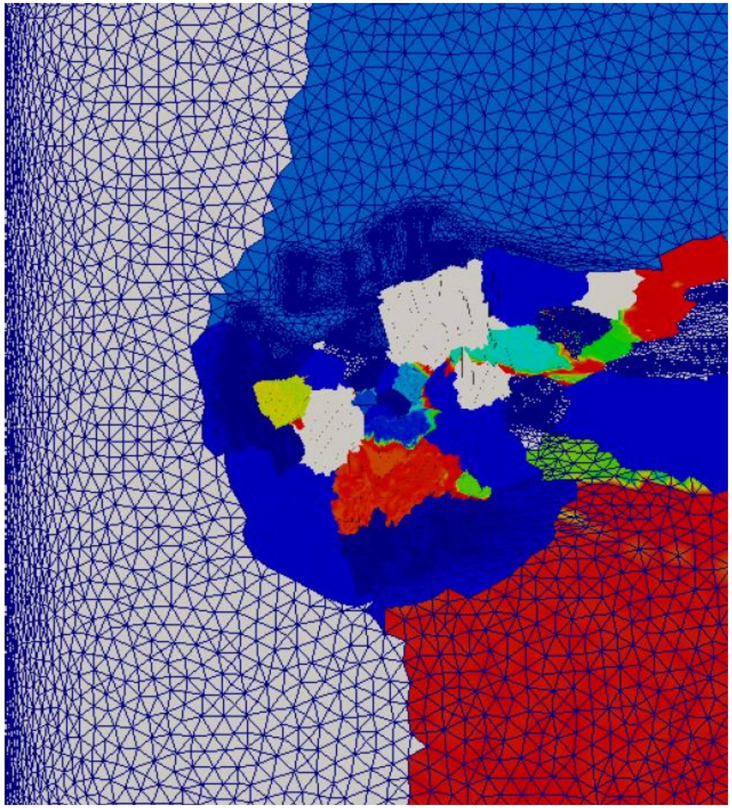
LSBU area





Horizontal slice of Reynold stress



32 sub-domains in different colours

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Construction of NIROM

Choose the POD basis functions

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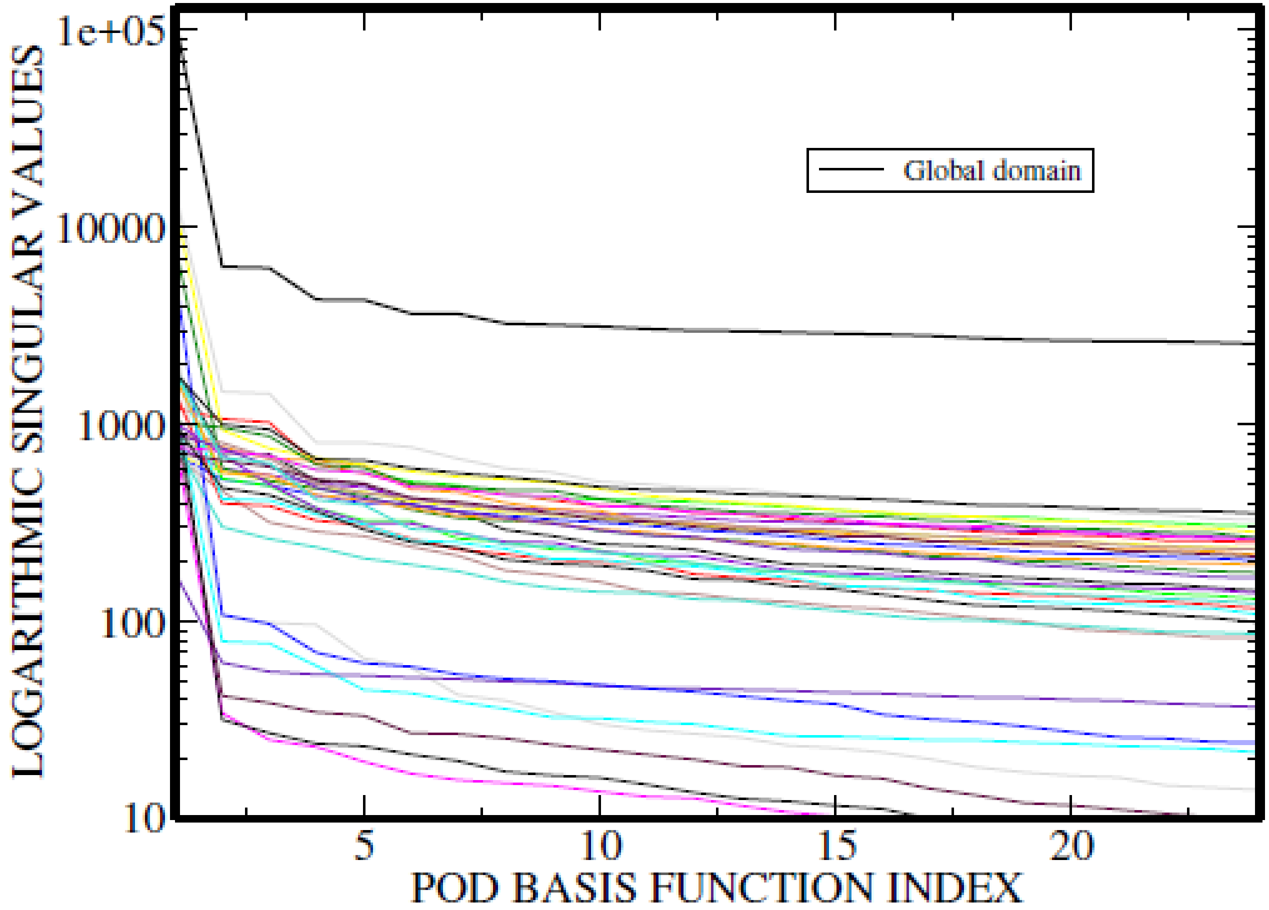

Comparison of velocity solutions between the NIROM and full model

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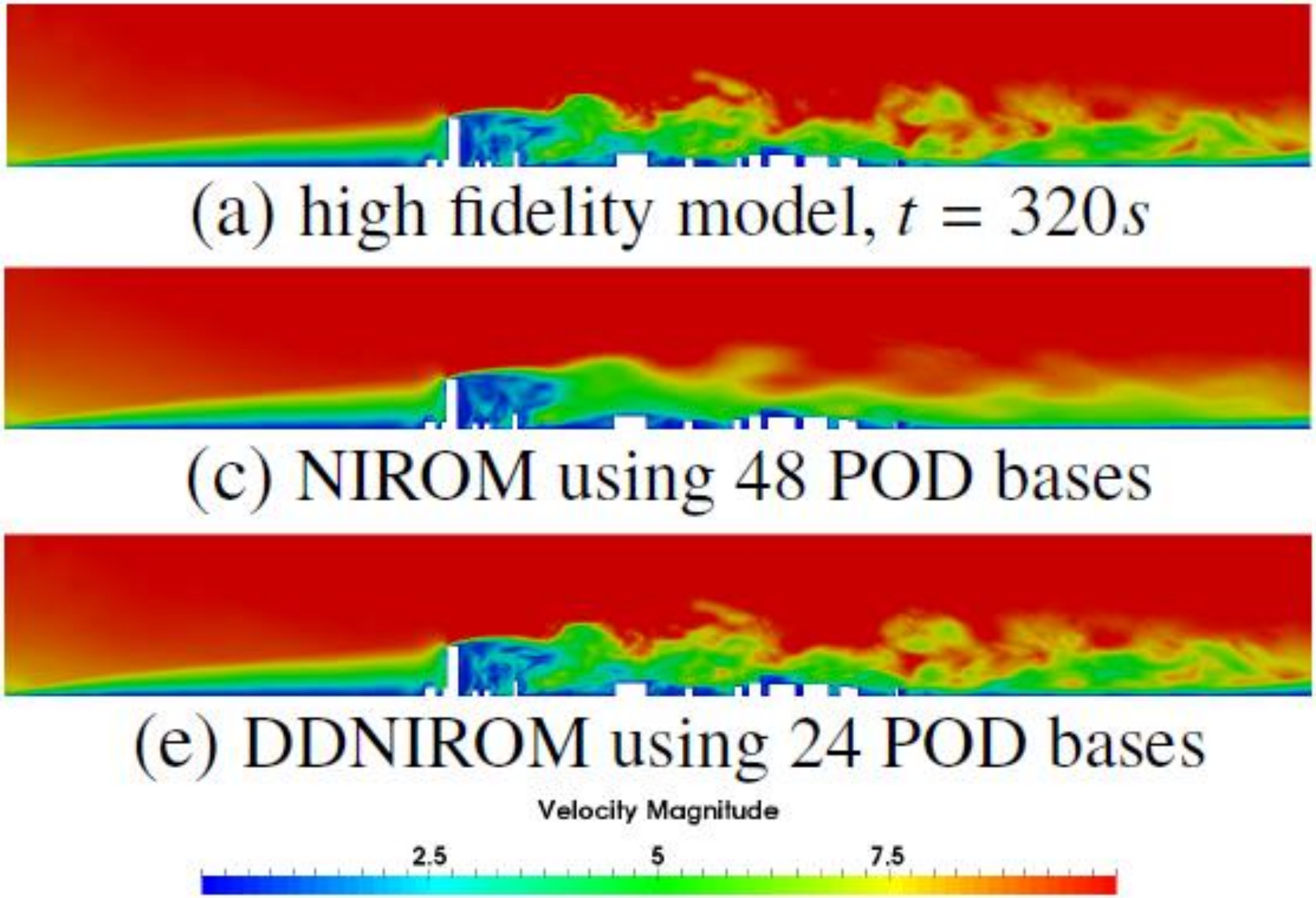

Probability density functions of x- velocity component

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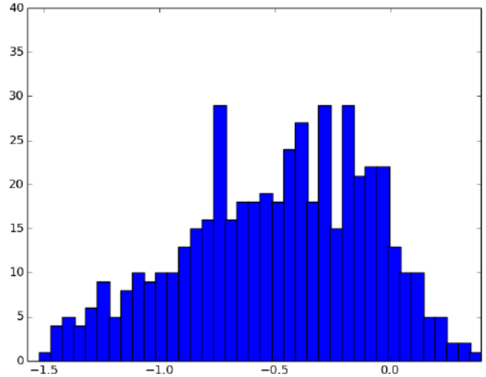
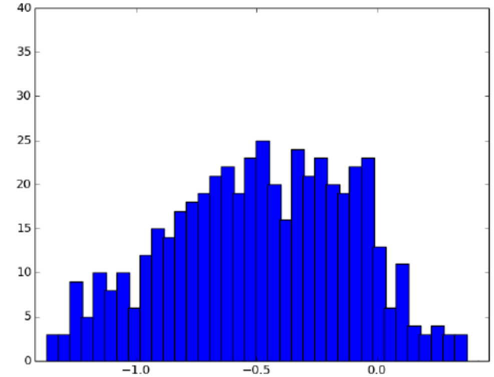
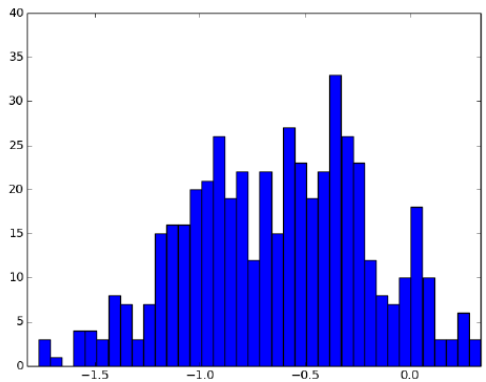


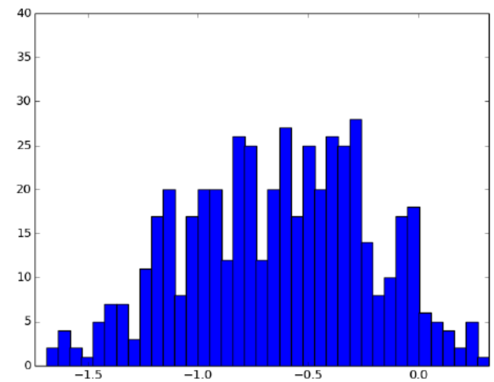
(a) high fidelity model at 10 m above the ground



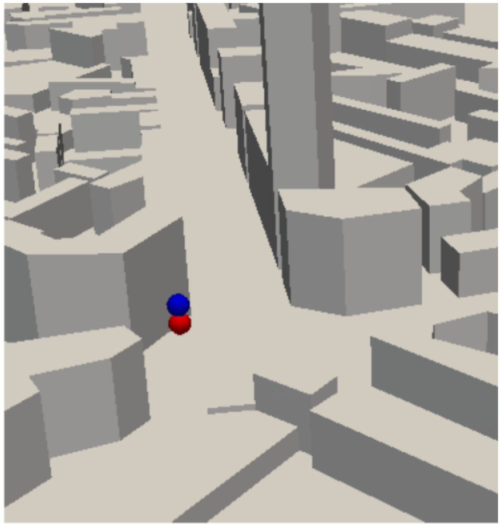
(b) DDNIROM 10 m above the ground



(c) high fidelity model at 5 m above the ground



(d) DDNIROM 5 m above the ground



NIROM in traffic modelling

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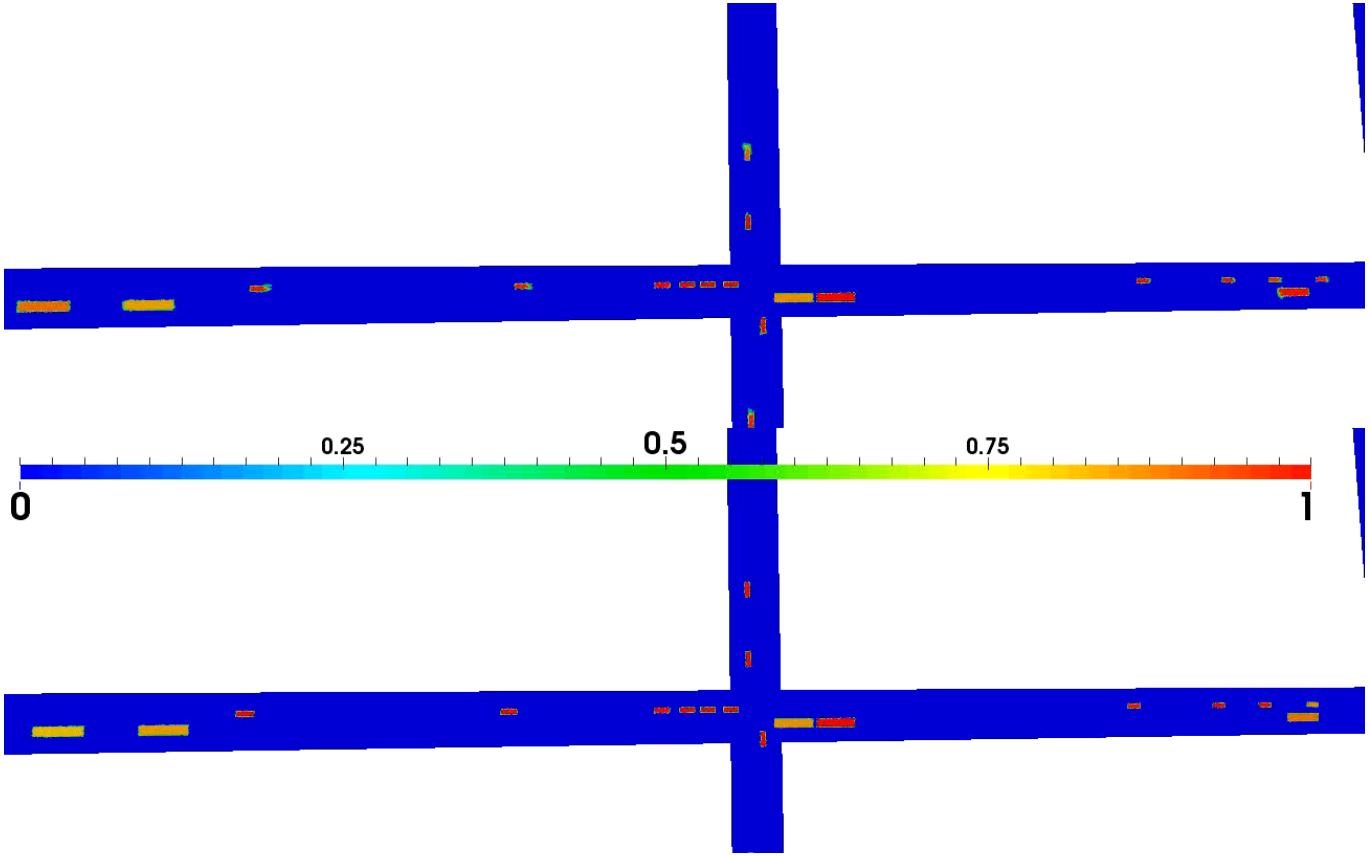

Conclusion and future work

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Conclusion

The computational cost is reduced by 4 order of magnitude while remaining the accuracy of results and catching the details of local turbulent flow features.

Next Focuses (accuracy, robustness, predictive capability)

A parametric NIROM for LSBU (varying boundaries condition, initial conditions, different direction of wind).

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Joint work from our research partners: Large scale atmospheric and air pollution modelling (IAP/IUE/ICL)

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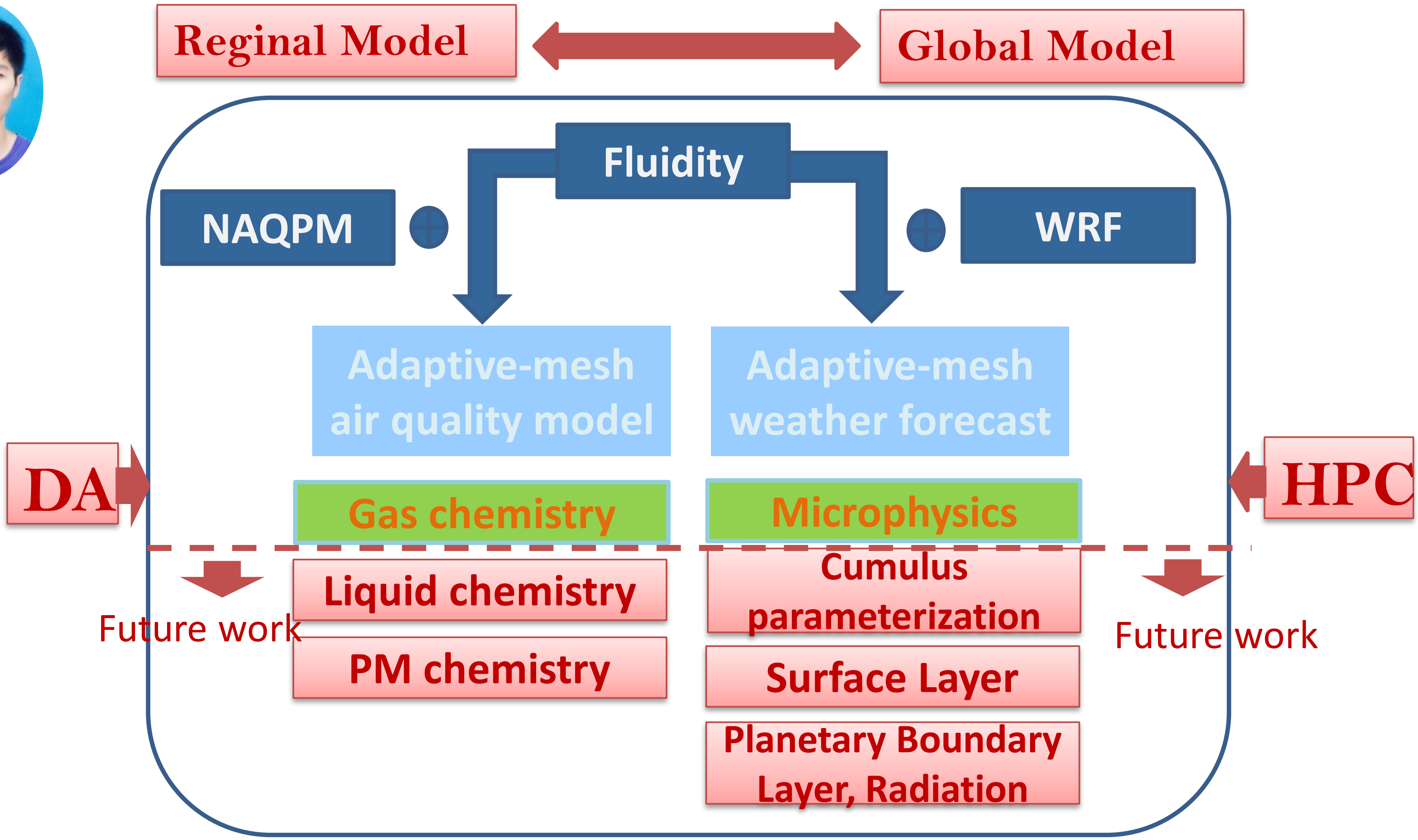

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