Simulating microscale meteorology in urban environment

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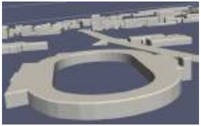
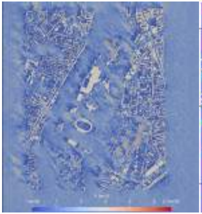
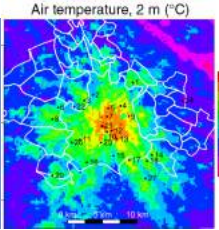
The multiscale nature of urban units

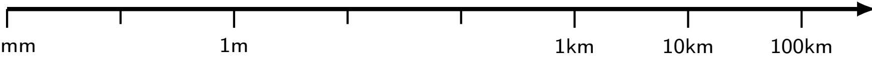
Climate scales	Microscale			Mesoscale
Urban units	Constitutive elements	Building	Neighbourhood	City/Urban region
Model categories	BC-HAM	CFD/BES	CFD/MMM	NWP/MMM







Kwok et al. (2019)



Characteristic horizontal distance scale (m)

Adapted from Oke et al. (2017)

The multiscale and multiphase nature of the urban phenomena

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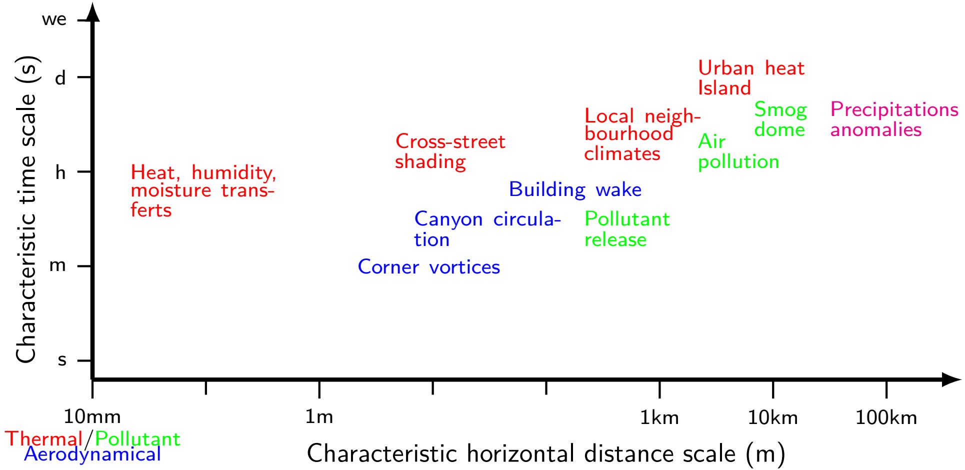

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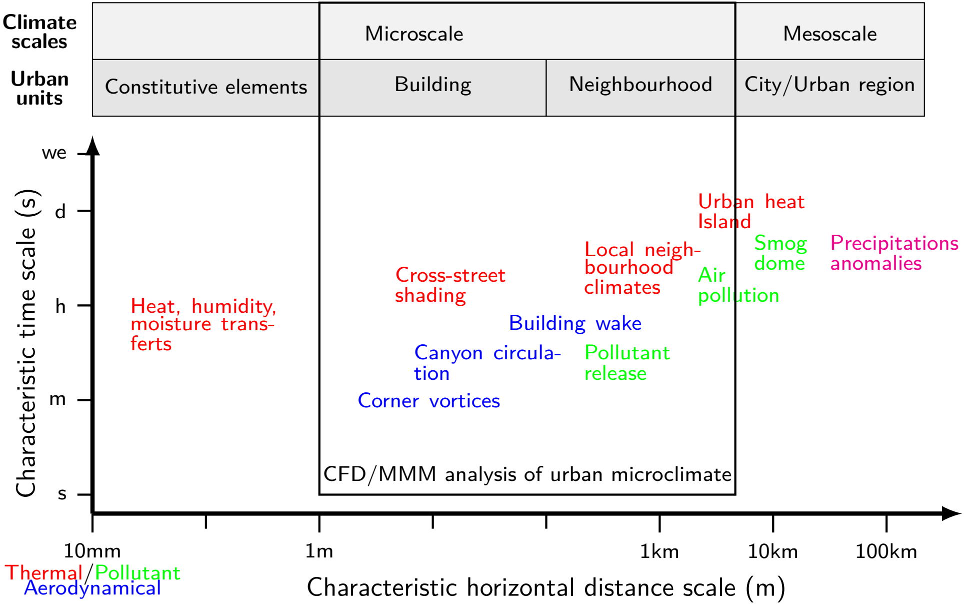
The multiscale and multiphase nature of the urban phenomena



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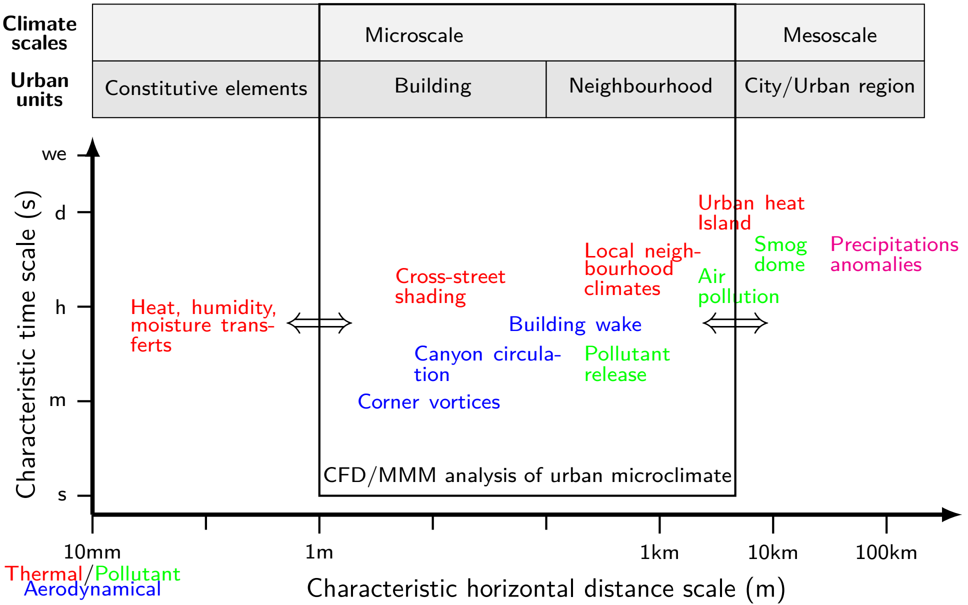
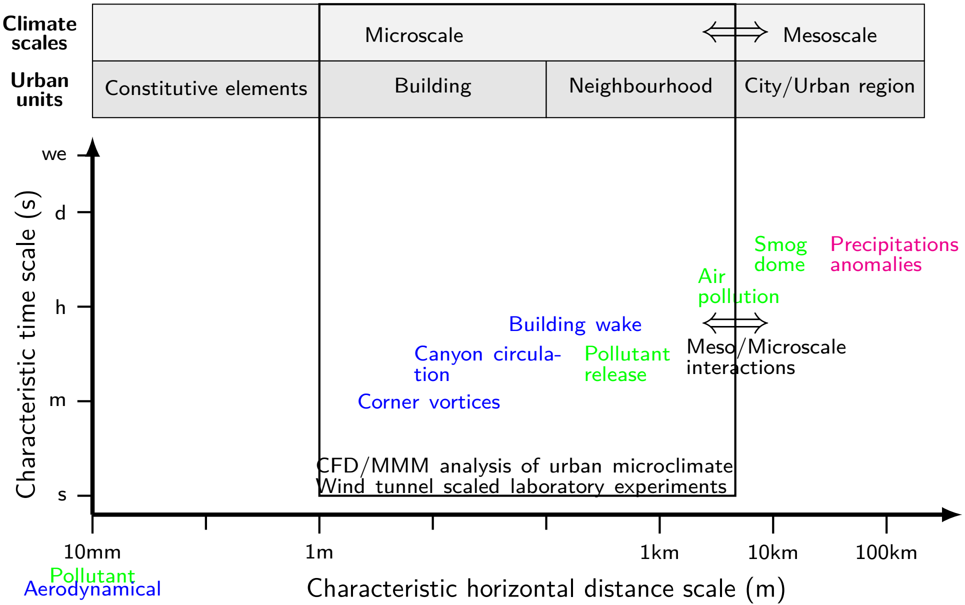


Adapted from Oke et al. (2017)

Neutral or near-neutral assumption



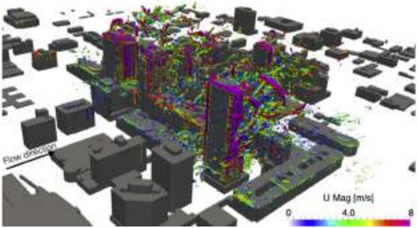
Adapted from Oke et al. (2017)

Wind tunnel scaled laboratory exp.

Klein et al. (2007)

- controlled boundary conditions
- numerous measurements possible
- model validation

CFD models



García-Sánchez et al. (2018)

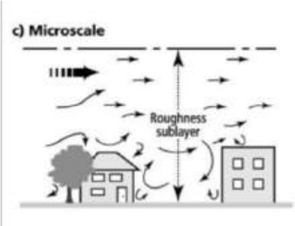
- able to simulate airflow structures around obstacles

Real field exp.: JU2003 (Allwine et al., 2004), MUST (Yee and Biltoft, 2004)

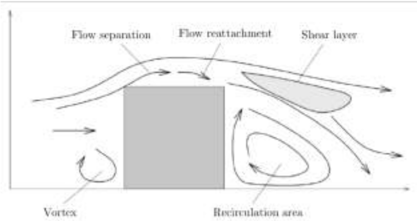
Wide range of turbulent scales involved at microscale

- large-scale fluctuations (meso-scale conditions)
- small-scale fluctuations (wind shear, interaction with obstacles)

leading to flow separation and reattachment, vortex/recirculation areas, ...



Oke (1997)



Turbelin (2000)

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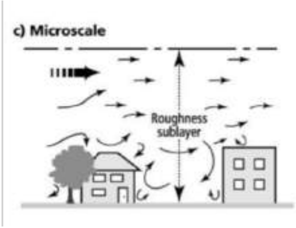

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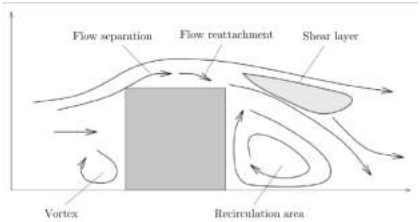
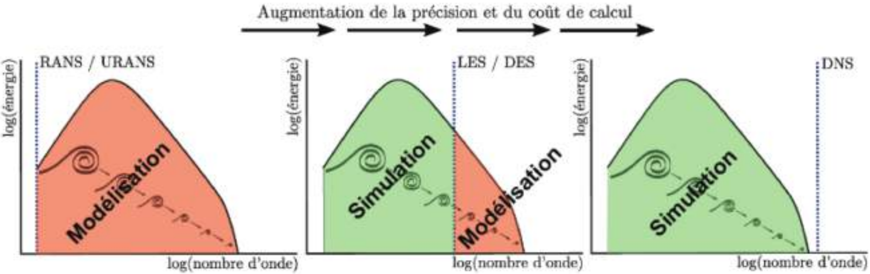


Turbelin (2000)

that challenge CFD modelling approaches:

- highly turbulent flows
- very fine resolution required to solve flow/obstacle interactions
- complex geometry
- large computational domain and time period

Large-eddy simulation (LES) promising to simulate microscale urban flows



Adapted from Lemay, Université Laval (2010)

RANS

- mean flow conditions
- Reynolds-averaged Navier-Stokes equations
- turbulence model

LES

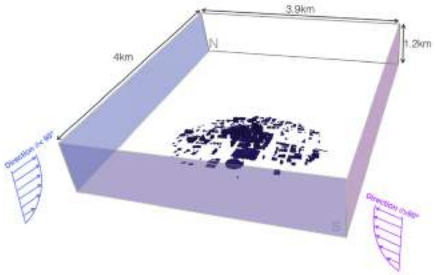
- mean/high-order flow statistics
- filtered Navier-Stokes equations
- subgrid-scale turbulence model

DNS

- full turbulent spectrum
- limited computational domain and time
- impracticable for urban flows

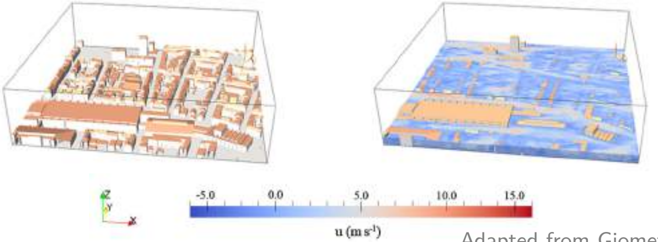
State-of-the-art LES of urban flows

- Developping boundary-layer



Adapted from García-Sánchez et al. (2017, 2018)

- Periodic boundary conditions



Adapted from Giometto et al. (2016)

But discrepancies between laboratory and field experiments!

Klein et al. (2007)

Allwine and Flaherty (2006), Joint Urban Oklahoma City experiment 2003 (JU2003)

- Non-negligible differences between measured wind speed/direction or pollutant concentration, e.g. JU2003 (Klein et al., 2007)
- The inherent variability in the Atmospheric Boundary-Layer (ABL) may induce these discrepancies $\rightarrow$ the boundary conditions of a field experiment cannot be controlled, and the ABL large-scale variability prevents the acquisition of time-series representative of the quasi-steady flow conditions in wind tunnel experiments (Dauxois et al., 2021).
- Also true for CFD models (García-Sánchez et al., 2018; Dauxois et al., 2021)

Main issue with LES of urban flows (Dauxois et al., 2021):
How to account for the ABL intrinsic variability in the boundary conditions of urban areas?

- Data-driven approaches
- Using turbulence recycling, precursor and grid-nesting with LES models
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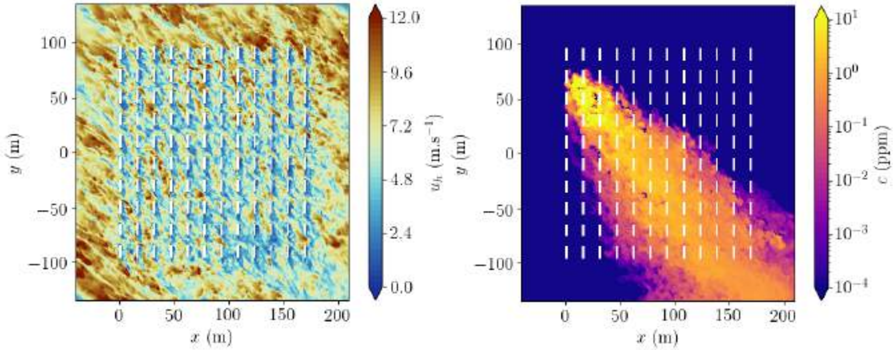
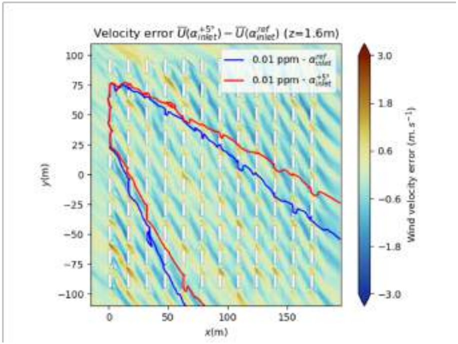
Illustration of the data-driven approaches through the MUST field experiment

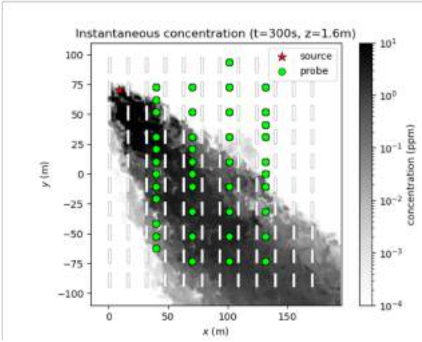


Lumet et al. (in preparation)

- LES model: AVBP (Gicquel et al., 2011)
- Subgrid-scale turbulence model suitable for flow/wall interactions: WALE (Nicoud and Ducros, 1999)
- Synthetic turbulence generation to have realistic inflow boundary conditions
- Unstructured mesh of 90 millions tetrahedra (refinement near obstacles)
- Computational cost: 20,000 CPU hours for 260 s

Promising LES approach but uncertainties



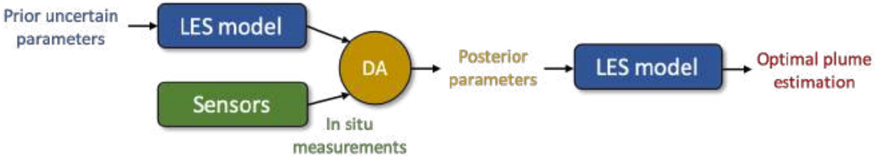


Lumet et al. (in preparation)

- Uncertainties at upstream meteorological stations may not be representative of actual conditions for the microscale domain

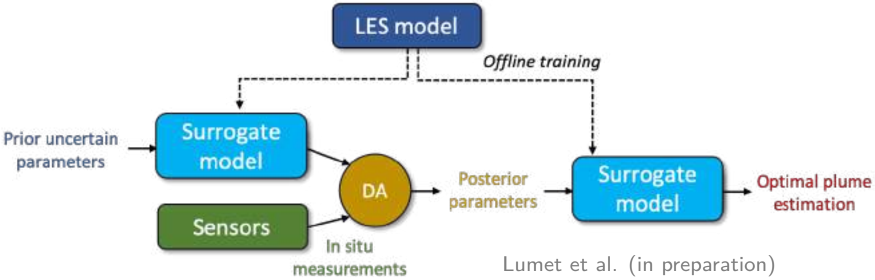
- Large impact of uncertainties in wind velocity and wind direction
  → **Need to reduce uncertainties in inflow boundary conditions through data assimilation** (e.g. Sousa and Gorlé, 2018, 2019; Defforge et al. 2021; Lumet et al. in preparation)

Designing a data assimilation approach suitable for a LES model



- **Data assimilation problem:** estimate best the mean concentration field given concentration observations and LES model predictions
- **Two main issues linked to the LES model:**
  - LES models depend more on boundary condition parameters than on initial condition → **Bayesian Inference of inflow parameters:** (1) wind direction and (2) friction velocity

Designing a data assimilation approach suitable for a LES model



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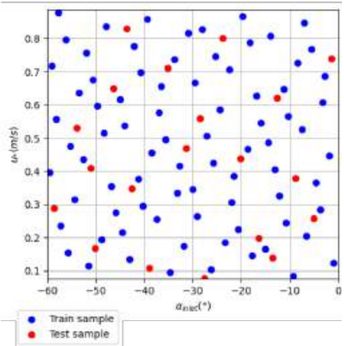
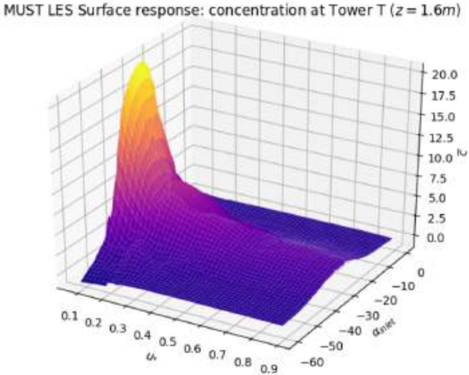
  - LES models are too costly to be used in the data assimilation loop → **Replace the LES model by a surrogate model** (emerging idea: Nony et al. in review)

Learning the spatial variability from LES using machine learning





Lumet et al. (in preparation)

- **Machine learning approach:** radial basis functions (hyperparameter fitting)
- **Budget of 100 LES** for a proof of concept (80% training, 20% test)
- **Cost-effective mean concentration prediction:** 0.125 s for 1 surrogate evaluation

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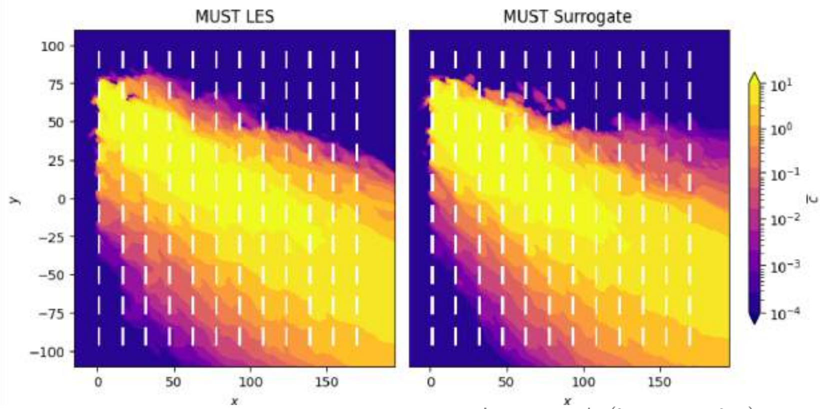

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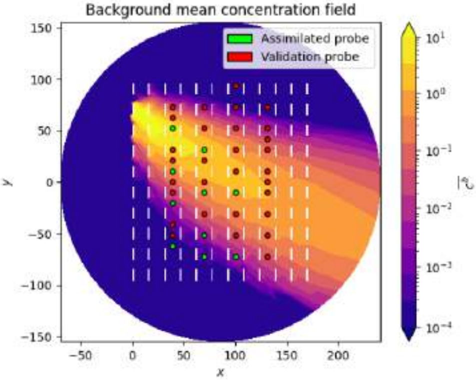
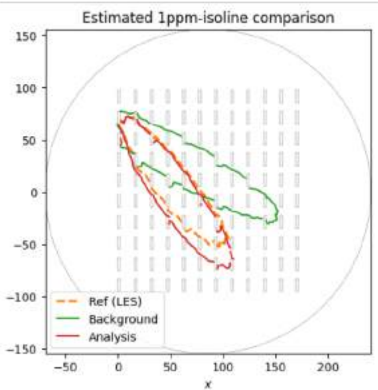
Example of surrogate-based data assimilation results



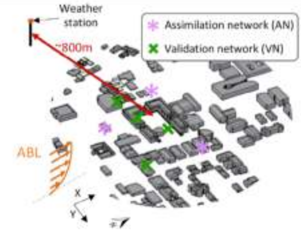


Lumet et al. (in preparation)

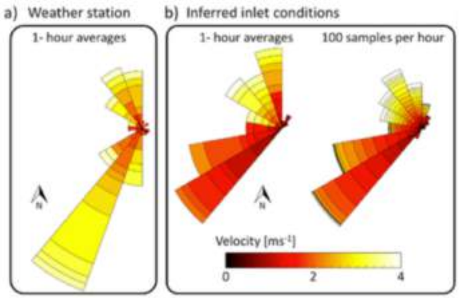
Very satisfying results but

- small shift in the plume axis between reference and estimation
- larger discrepancies for high concentration values (more difficult to infer the friction velocity)
- sensitivity to the choice of the comparison metric (concentration specificity)

Example of data assimilation application to real city configuration



Sousa and Gorlé (2019)



- Field measurement campaign on Stanford's campus (sonic anemometers)
- Data-driven strategy: polynomial chaos surrogate combined with ensemble Kalman filter (limitation to RANS simulations)
- Significant improvement of urban wind flow predictions using data assimilation compared to using standalone weather station data

→ **Data assimilation provides a promising framework to reduce inflow boundary condition uncertainties and improve wind flow predictions in a full-scale urban environment.**

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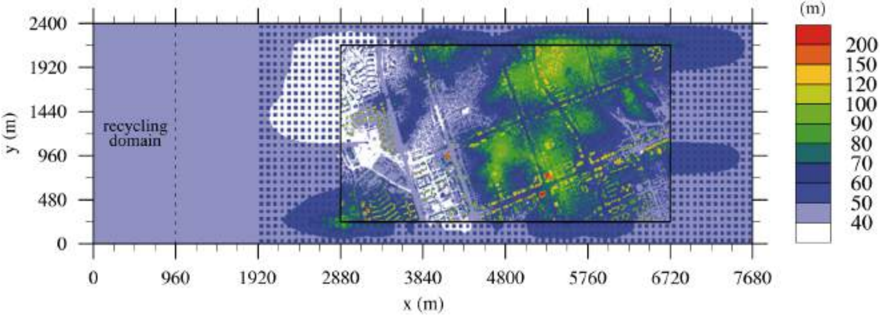
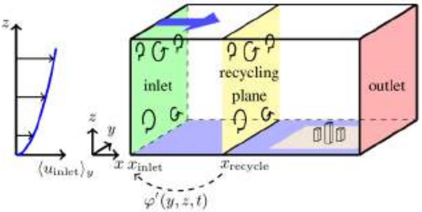
Using turbulence recycling and precursors with LES models

Park et al. (2013): Application of PALM (Maronga et al., 2015) on Seoul area

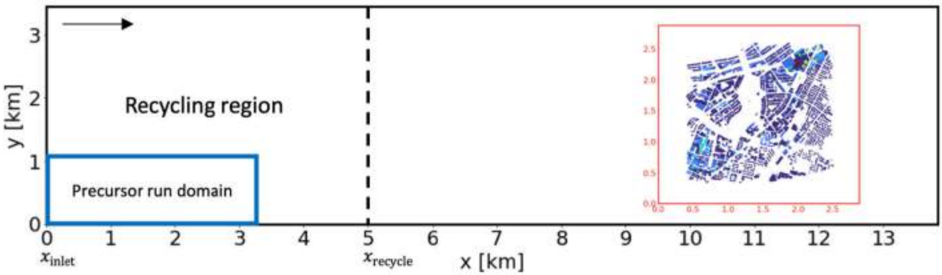


- Initial mean vertical profiles obtained from a precursor simulation.
- Turbulence recycling (Maronga et al., 2015).
- Use of buffer regions.
- Turbulent variability but not representative of the ABL large scales.



Using turbulence recycling, precursors and grid-nesting with LES models

Akinlabi et al. (2022): Application of PALM (Maronga et al., 2020) on Boston



- Grid-nesting: parent domain Δx=8m, child domain Δx=4m.
- Long parent domain: allows development of large-scale streamwise structures that can be found in neutral ABL (Hutchins and Marusic, 2007; Anderson, 2016).
- Does not capture all the large-scale structures.
- Recycling method may present issues when the flow direction changes and is not easily generalized for multiple inflow boundaries.

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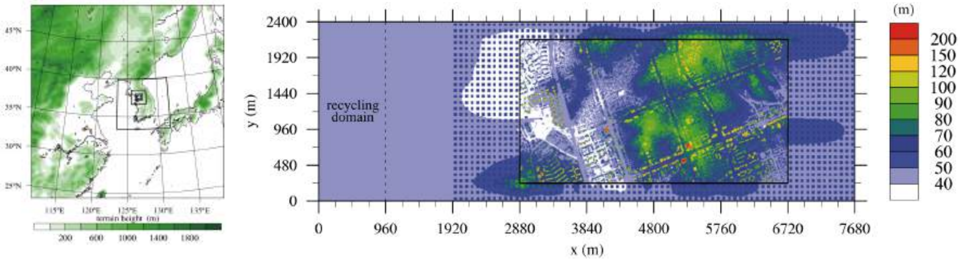
Coupling with a Numerical Weather Prediction model

- Park et al. (2015): coupling PALM and WRF (Skamarock et al., 2008) on Seoul



- Li et al. (2018): coupling in-house LES model and WRF on Oklahoma City
- Improves urban flow and dispersion results relative to microscale-only simulations.
- Important shortcomings:
  - Differences in governing equations, coordinate projections, grid systems, advection schemes, and parameterizations.
  - Requires a turbulence reconstruction method.
  - The quality of the solution strongly depends on the accuracy of the larger-scale simulation.

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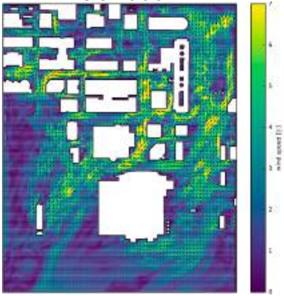
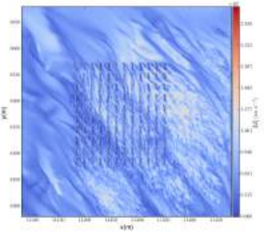
Using a Mesoscale Meteorological Model able to solve flow around buildings

- Wiersema et al. (2020): using WRF on JU2003



- Nagel et al. (2022): using Meso-NH (Lac et al., 2018) on MUST



Using a Mesoscale Meteorological Model able to solve flow around buildings

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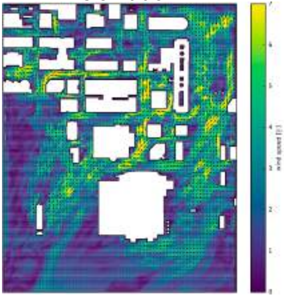

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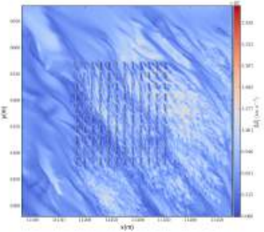
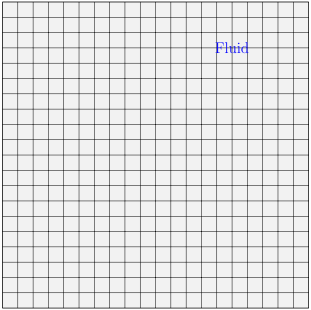


Immersed Boundary Method (IBM)

MesoNH-IBM: modify boundary conditions to impose 0-wind approaching obstacles (Auguste et al., 2019)



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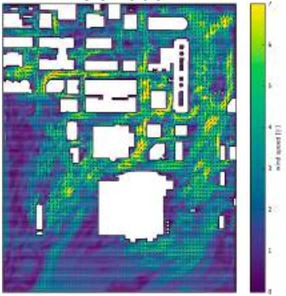

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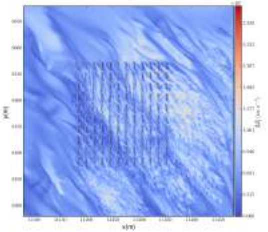

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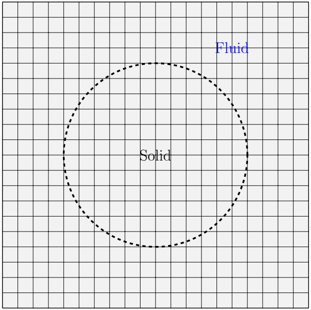
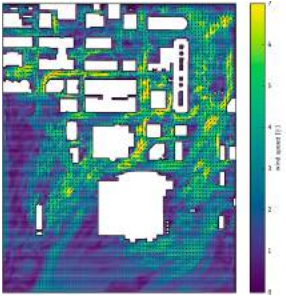


Using a Mesoscale Meteorological Model able to solve flow around buildings

- Wiersema et al. (2020): using WRF on JU2003



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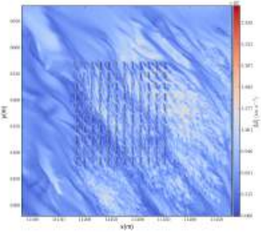

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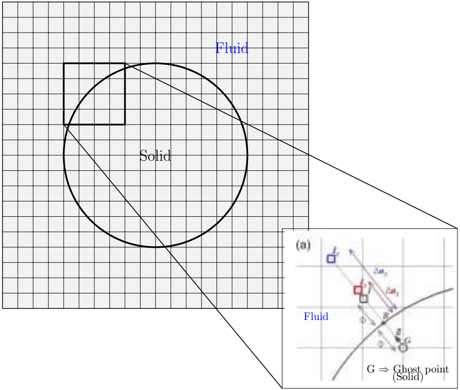
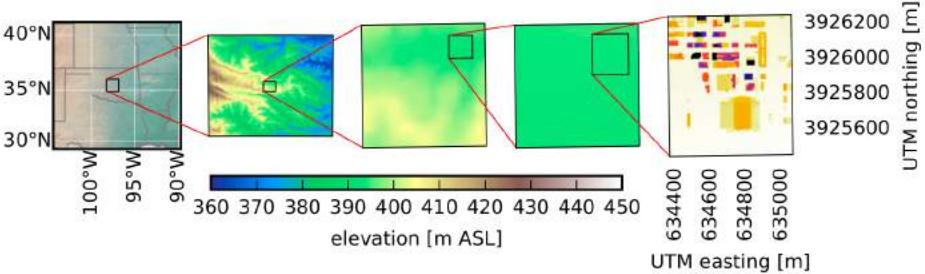


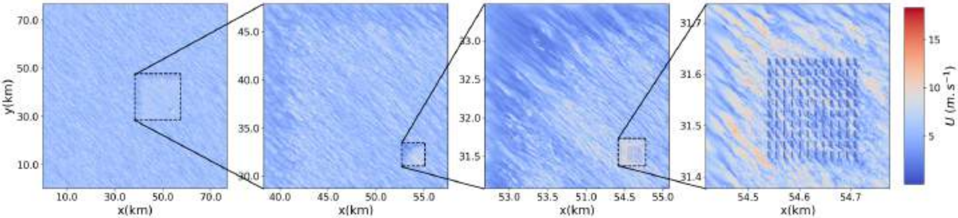
Modification of ghost points values → the fluid sees a solid. Boundary conditions are imposed at the fluid-solid interface.

Dynamic downscaling: allows to account for full ABL turbulence influence



Wiersema et al. (2020)

This approach can be used to provide prior information to data-driven approaches.



Nagel et al. (2022)

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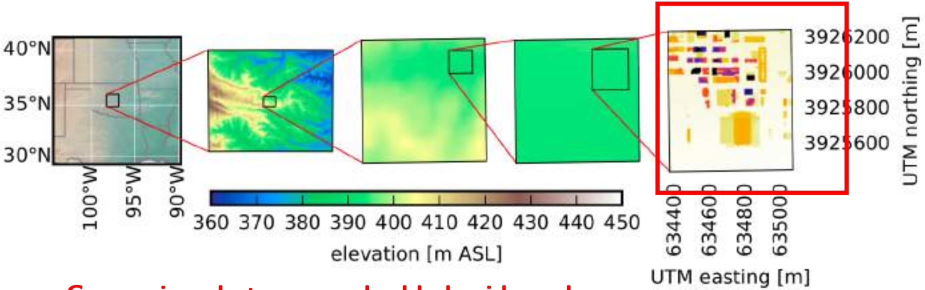
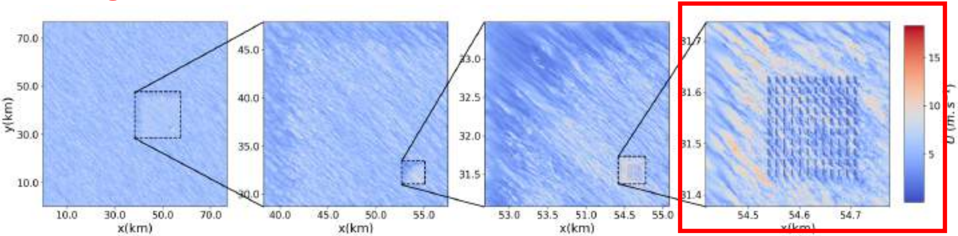


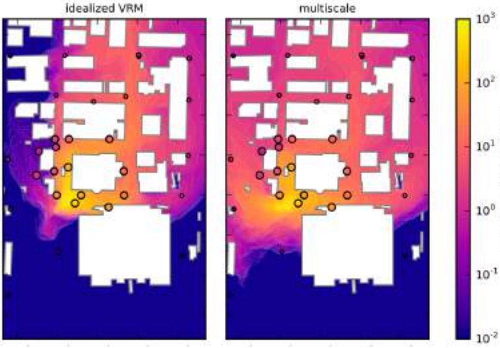
Wiersema et al. (2020)

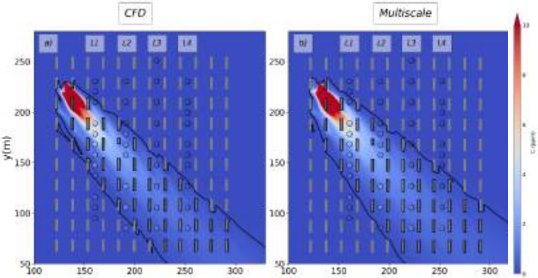
Comparison between embedded grids and single domain CFD-like



Nagel et al. (2022)

CFD-like vs Multiscale





- JU2003: Multiscale simulation outperformed idealized simulations for pollutant concentration metrics. Also good results on wind speed and direction.
- MUST: Microscale simulation of wind speed and pollutant concentration benefits from taking into account the ABL turbulence. However, this benefit is significantly less important than for JU2003.

→ **The city configuration plays an important role:** idealized for MUST vs real city for JU2003

→ **Idealized models using generic buildings like MUST are too simple to properly represent the complex phenomena that drive pollutant transport in real cities.**

Urban heterogeneity: how to account for a realistic AND general representation of the urban environment?

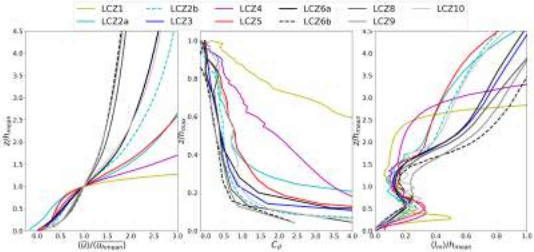
Urban heterogeneity: how to account for a realistic AND general representation of the urban environment?

- Real city: their complexity makes it difficult to distinguish the general impact of buildings from those induced by the city specific configuration.
- Idealized city: cubes or rectangles, aligned or staggered. Often too simple.
- Configurations based on urban classifications like Local Climate Zone (LCZ):

LCZ2: Compact midrise

LCZ4: Open highrise

LCZ5: Open midrise



Reference sectional drag coefficient and mixing length profile obtained for each urban morphology → LCZ-based parametrization.

Nagel et al. [in revision]

Conclusions and Perspectives

Climate scales		Microscale	⟺	Mesoscale
Urban units	Constitutive elements	Building	Neighbourhood	City/Urban region
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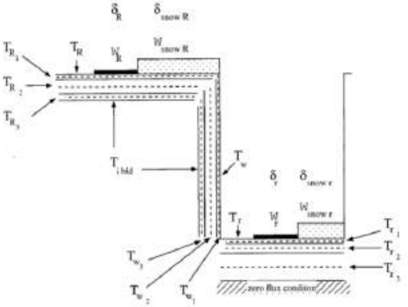
- MMM (Mesoscale Meteorological Model) can be used together with energy balance model for the town (Masson, 2000; Martilli et al., 2002).



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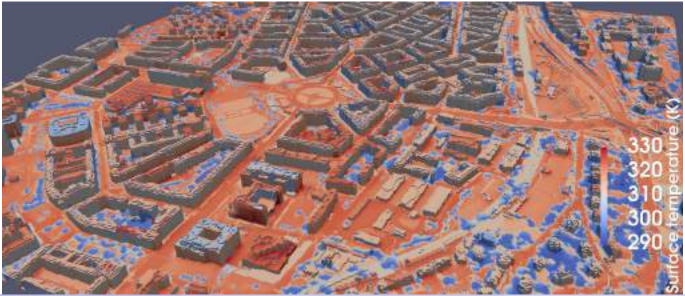

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- Starting in 2024: ANR-MC2. Coupling a Monte-Carlo spectral and directional radiative transfer model for complex urban canopies (Caliot et al., 2022) with MesoNH-IBM in order to perform multiscale and multiphysics simulations of town/atmosphere interactions.