Impact of Atmospheric Stability on Pollutants Dispersion in Urban Areas using a CFD-RANS Model

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Introduction

- High levels of pollutant concentrations are often recorded at the air quality monitoring stations in stable atmospheric conditions when the height of the PBL decreases.
- Better understanding of the behavior of horizontal dispersion of pollutants at street level in stable atmospheric conditions for planning effective strategies to mitigate urban air pollution.

Main objective

How to model the impact of the atmospheric stability on the pollutant dispersion using a CFD-RANS model?

The vertical distribution of meteorological variables is necessary ⇐ *Meteorological mesoscale model*

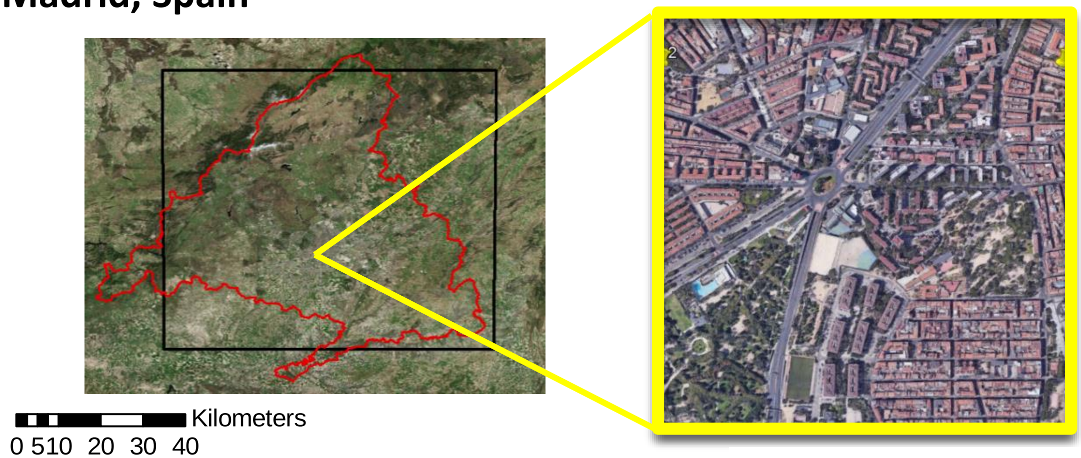
How to impose the vertical profiles from a mesoscale model into the CFD model?

1. The implementation of mesoscale vertical profiles into the CFD simulation
2. Sensitivity test of the impact of stable atmospheric conditions on pollutant concentrations using a CFD model

Modelling Approach

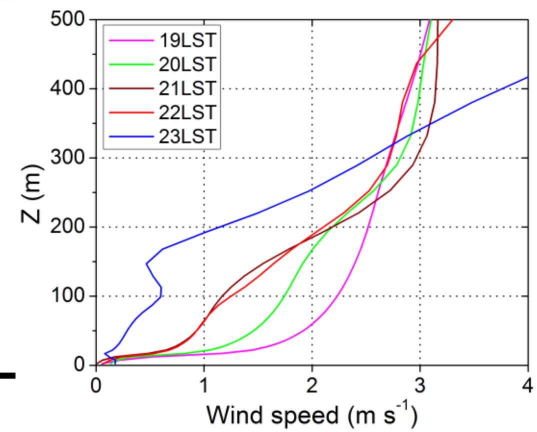
Mesoscale simulation: Weather Research and Forecasting (WRF) model with the urban parameterization (BEP-BEM)

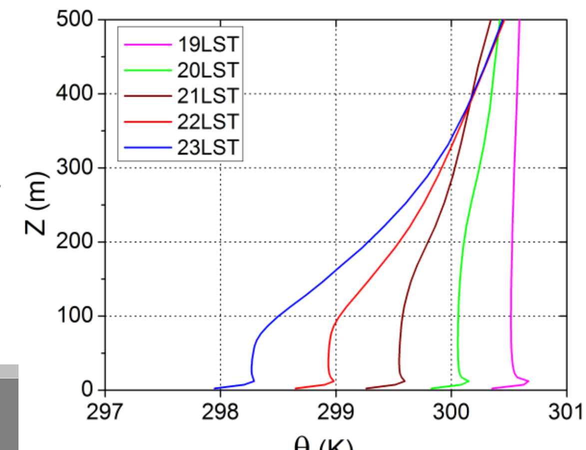
Madrid, Spain



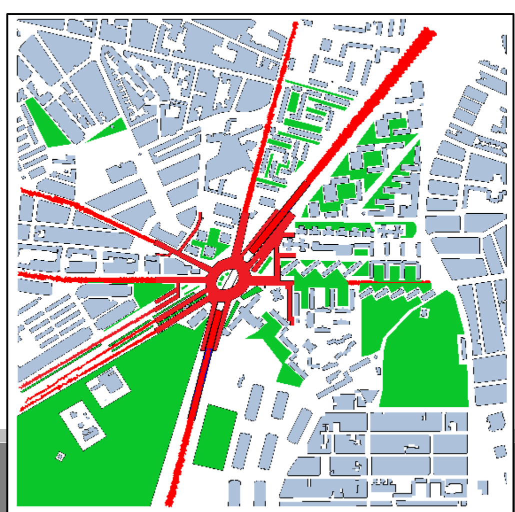
Inlet boundary conditions for the microscale simulation

Detailed vertical distribution of meteorological variables and its variation over time





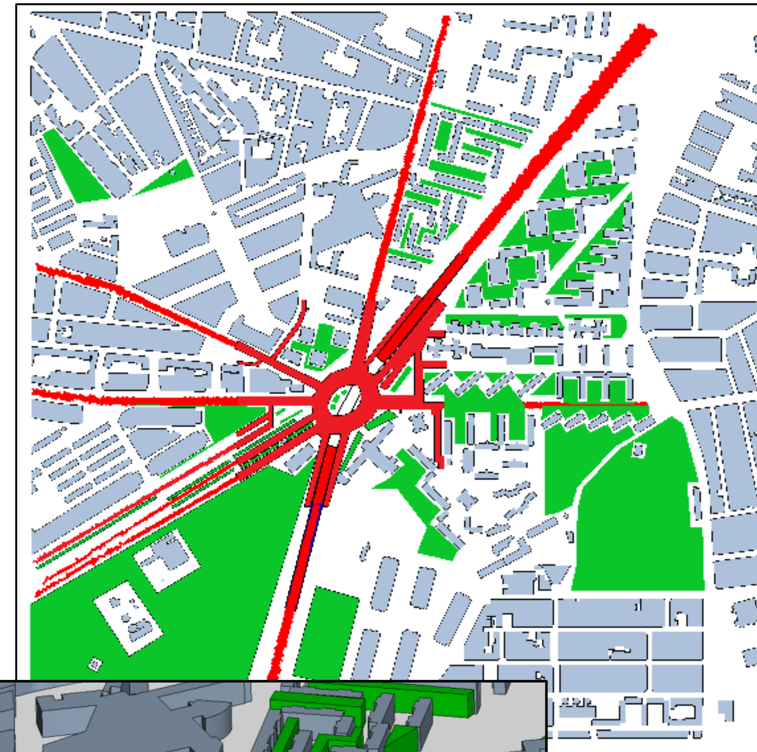
CFD simulation

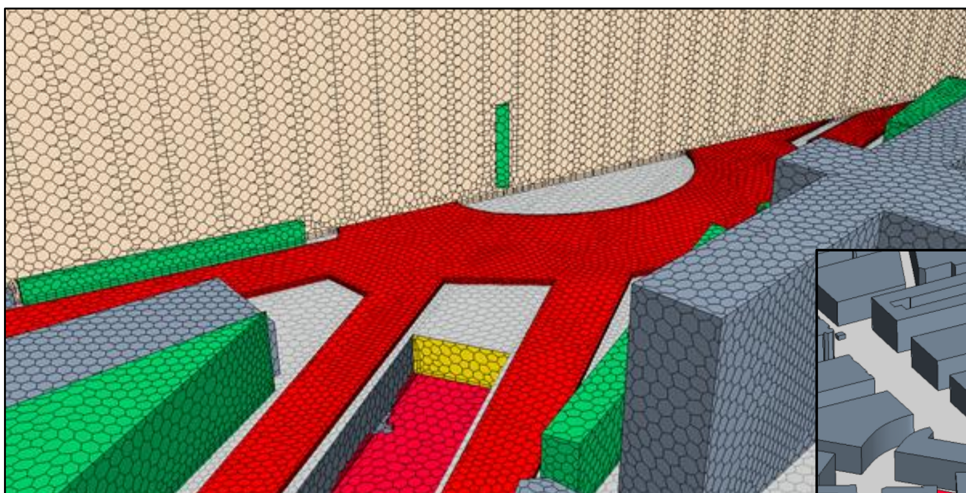


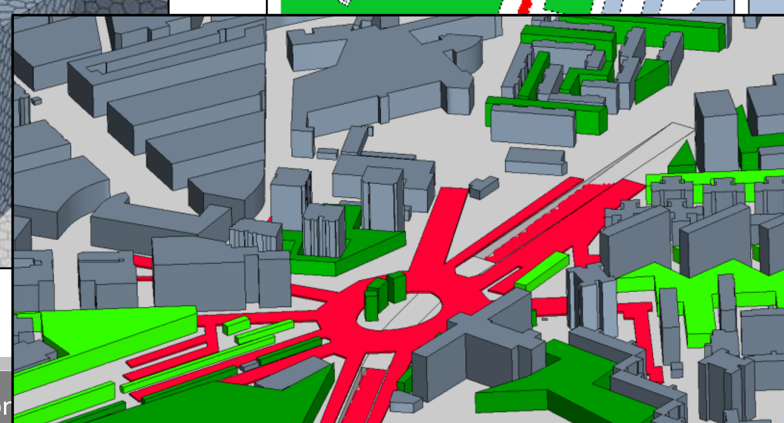
CFD Model Description

Numerical simulations are based on the Reynolds-averaged Navier-Stokes equations (RANS) with the Realizable *k-ε* turbulence closure assuming the Boussinesq approximation for modelling buoyancy effects.

- Domain: 1300 m x 1300 m x 900 m
- Polyhedral mesh: from 5 m at the boundaries to 2 m in the research area
- Traffic emissions: NO_x
- Aerodynamics effects of vegetation







Off-line coupling of the mesoscale results into the CFD simulation

- Transition zone between the boundaries of the domain and the buildings area.
- To adapt the inlet vertical profiles of the mesoscale variables in the CFD simulation.
- The drag force of buildings is imposed in the transition zone of the CFD domain as a volume with the mean height of buildings by means of:

$$S_{drag,u_i} = -\rho\, \alpha\, C_d\, |U|\, u_i$$

$$S_{drag,k} = \rho\, \alpha\, C_d\, |U|^3$$

$$S_{drag,\varepsilon} = \rho\, \alpha\, C_d\, |U|^3\, {}^{\varepsilon}/_{k}$$

$C_d = 1.85$ is the drag coefficient (*)

$\alpha = 0.0787\ m^{-1}$ is the vertical surface density of buildings

Depending on the wind direction

Study cases:

- Drag force of buildings
- Smooth ground

(*) Santiago and Martilli, 2010.

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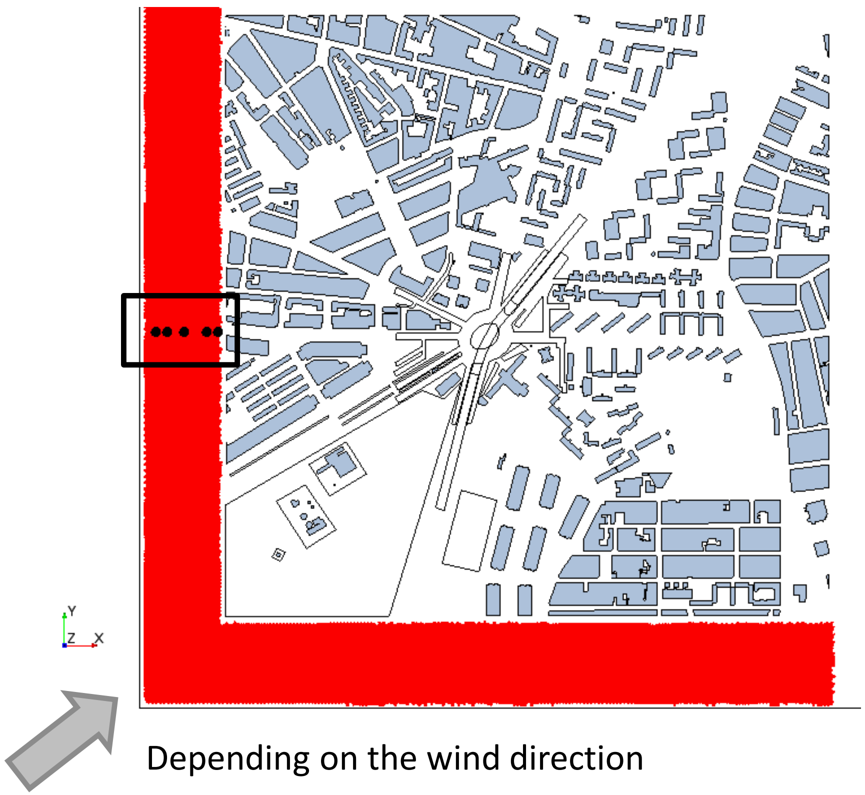

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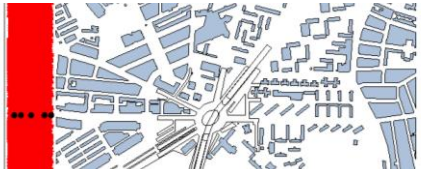
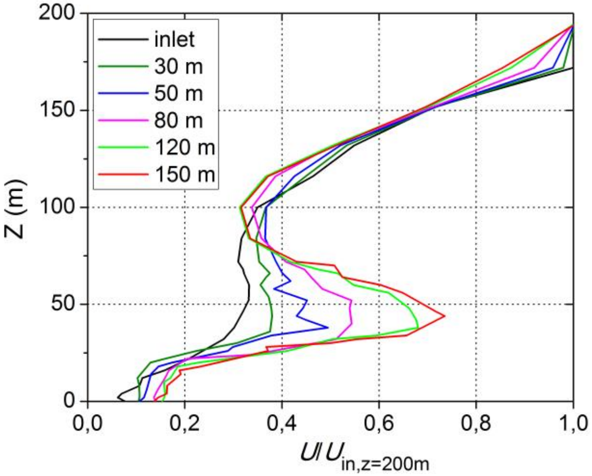
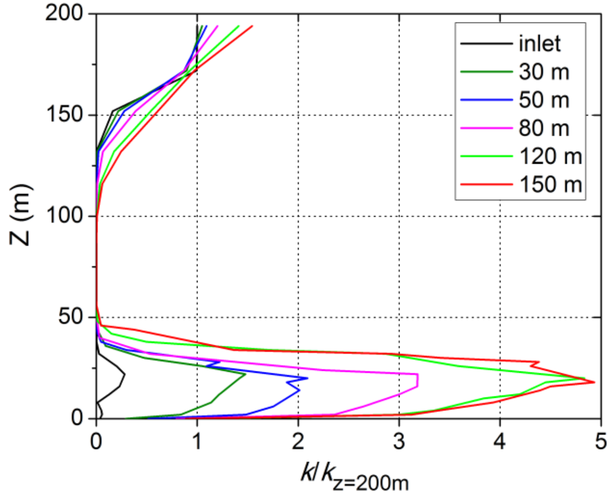
In stable atmospheric conditions: Vertical profiles at different distances from the inlet boundary:

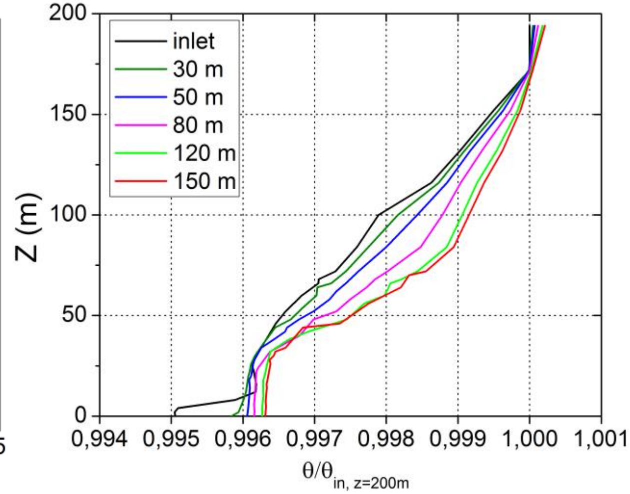


Drag force of buildings

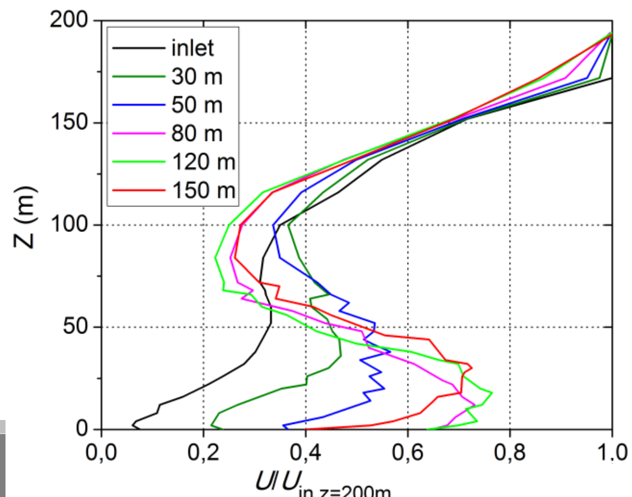
Normalized wind speed **Normalized Turbulent Kinetic Energy** **Normalized Potential Temperature**

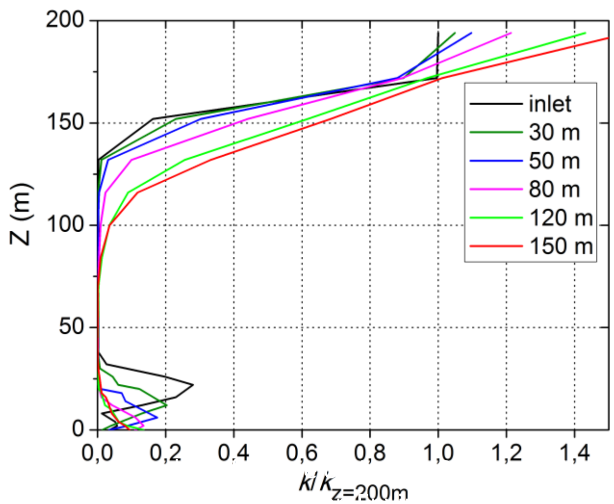


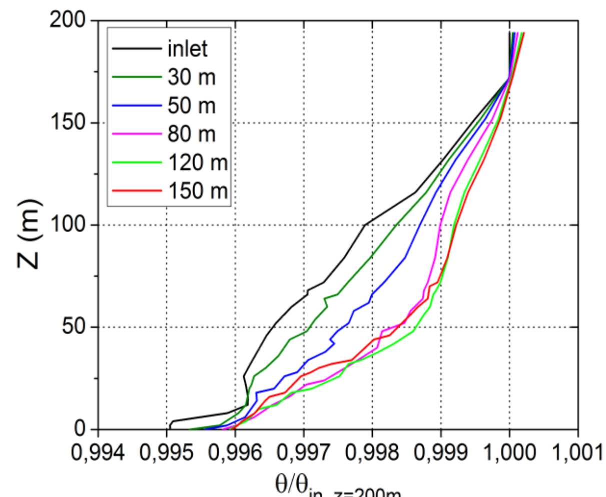




Smooth ground







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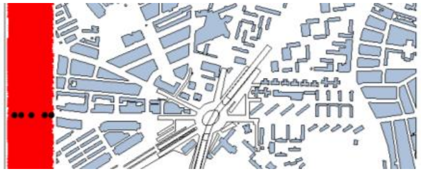
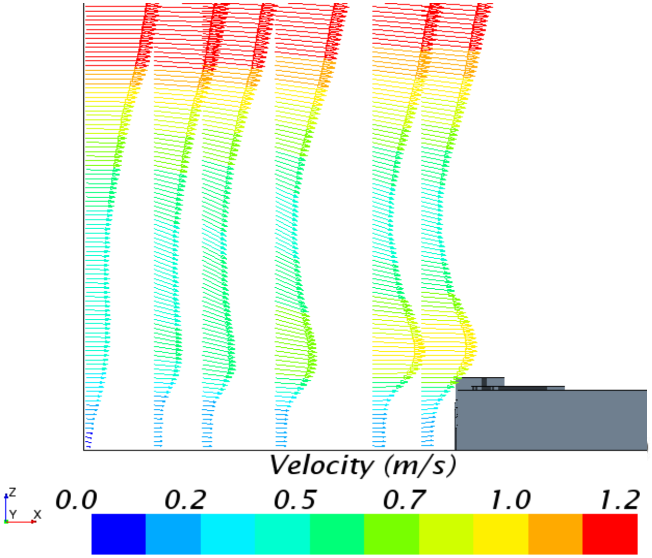
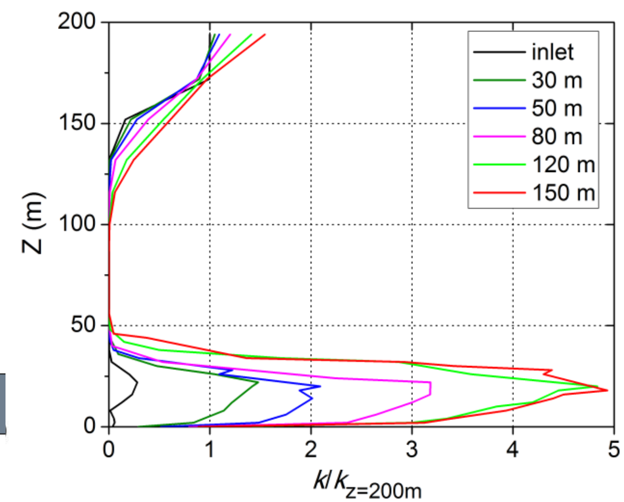
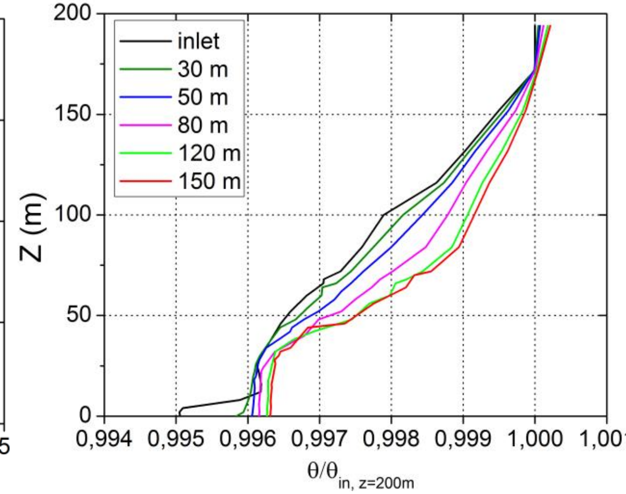


Drag force of buildings

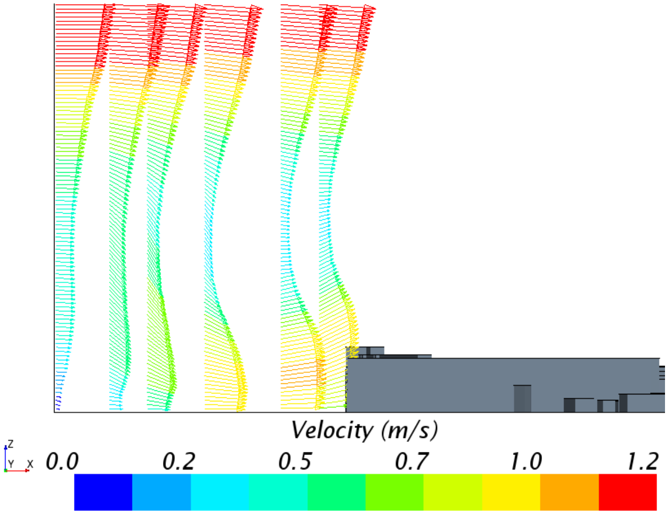
Normalized wind speed | **Normalized Turbulent Kinetic Energy** | **Normalized Potential Temperature**

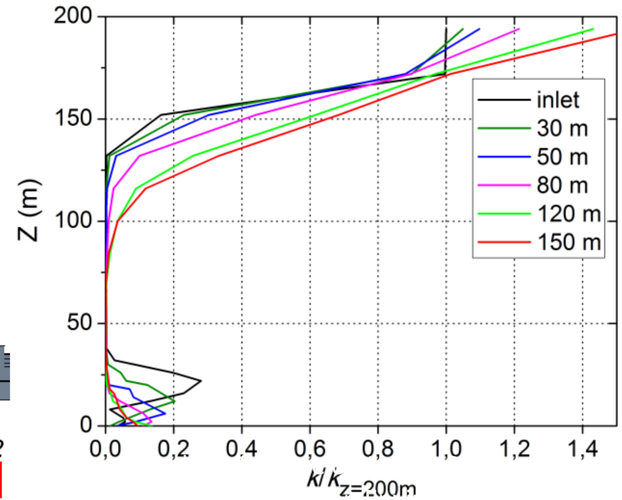


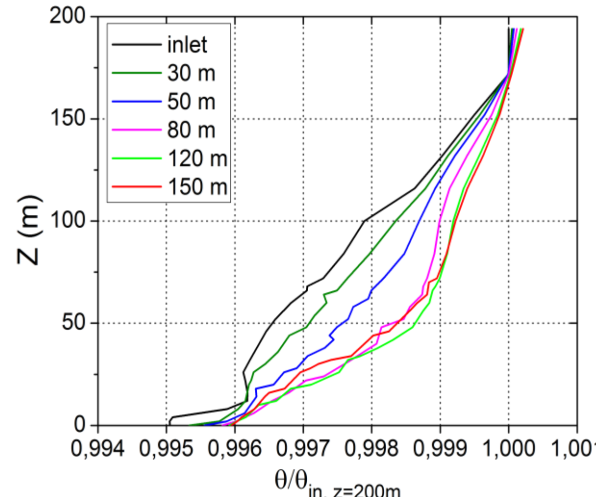




Smooth ground

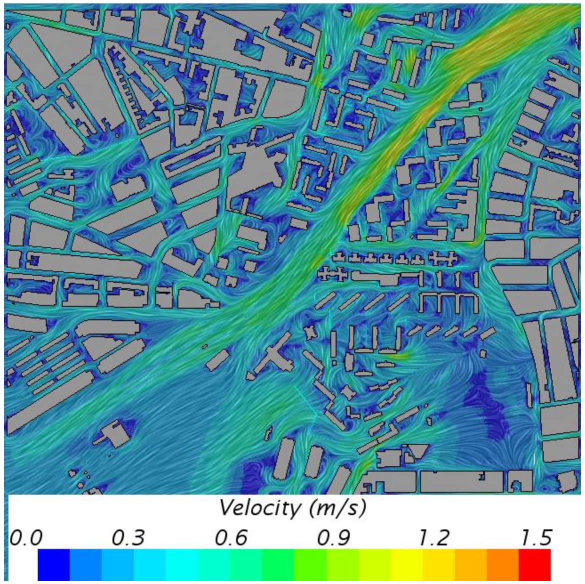




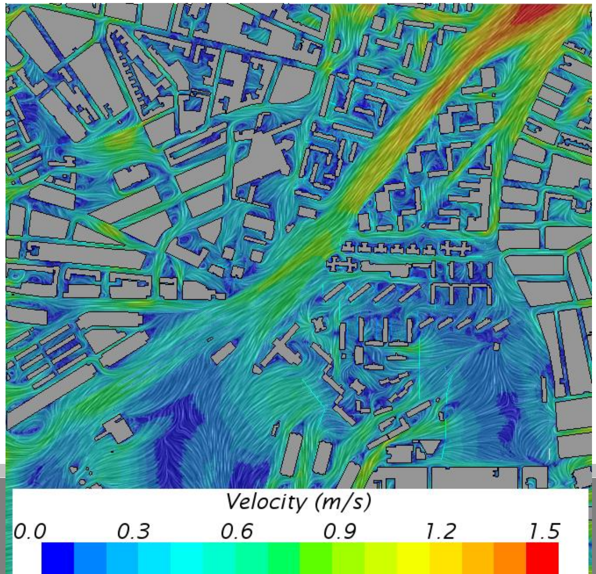


<u>At 3 m</u> in the research area:

Drag force of buildings

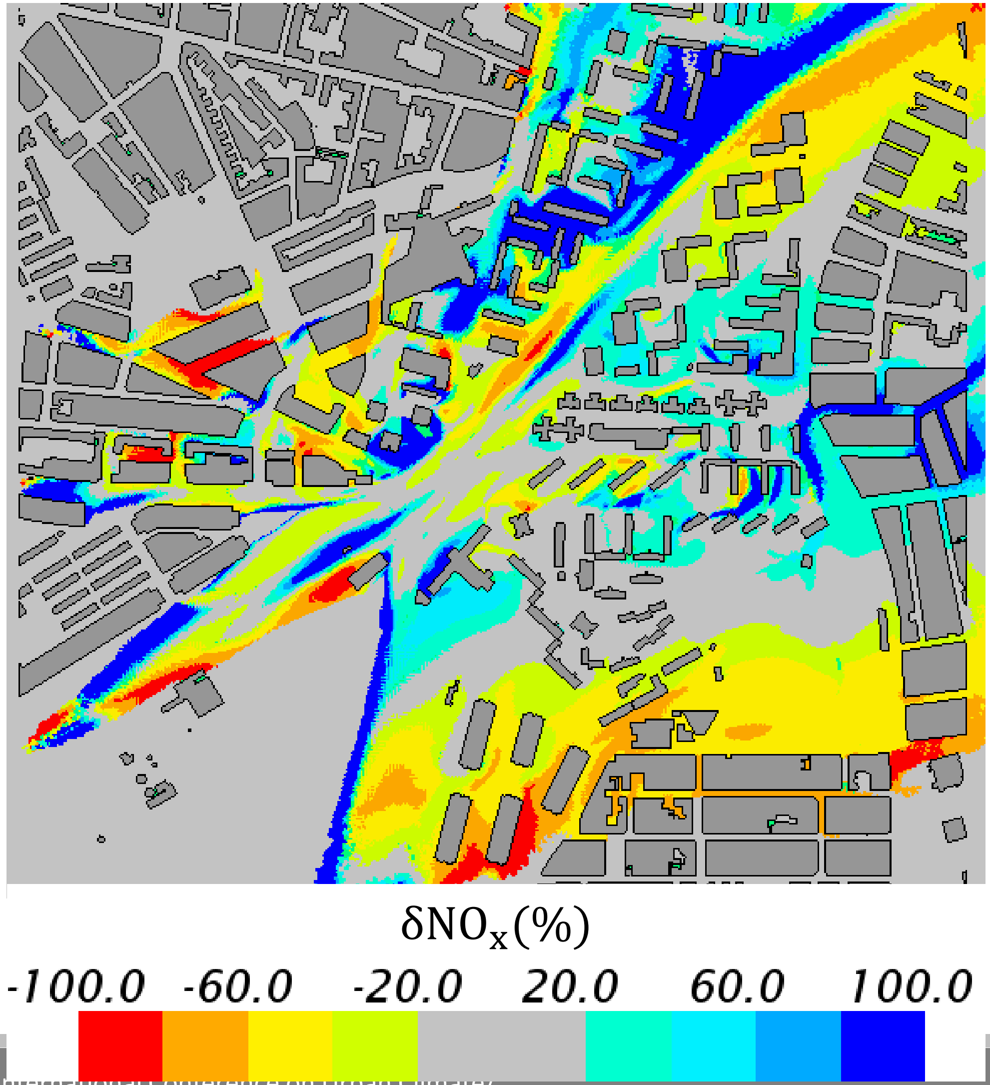


Smooth ground



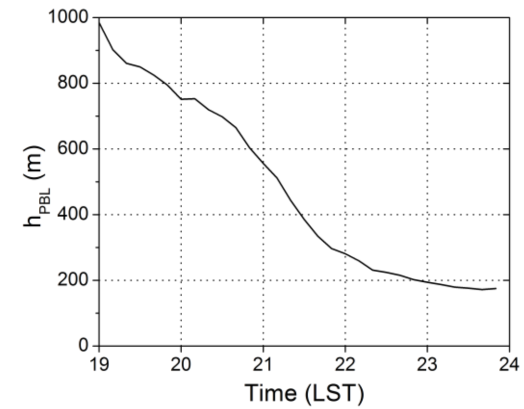
Relative difference of NO_x concentration

$$\delta NO_x(\%) = \frac{NO_{x,\,withInDrag} - NO_{x,\,withoutInDrag}}{NO_{x,\,withInDrag}} \cdot 100$$



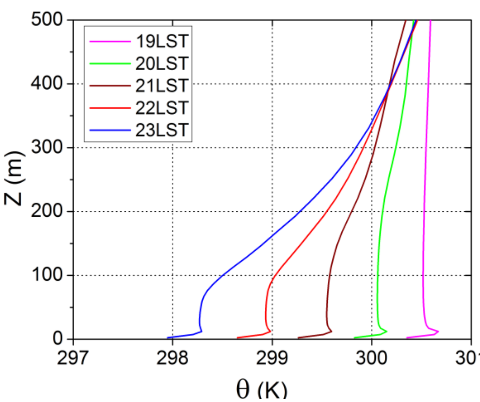
Impact of atmospheric stability on the pollutant dispersion

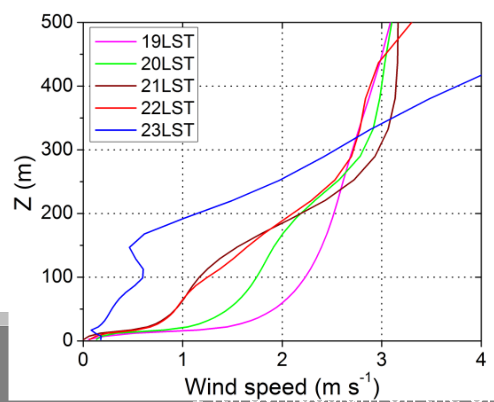
- The effect of the decrease of PBL height
- Unsteady simulation from 19LST to 00LST of 10th October, 2017
- Inlet conditions are changing every 10 min
- Sensitivity test of the NO_x concentration in an urban area to the meteorological conditions using the CFD model: neutral and stable
- Same wind direction from WRF



Neutral atmospheric conditions: $u_{in}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right); k_{in} = \frac{{u_*}^2}{{C_\mu}^{1/2}}; \varepsilon_{in}(z) = \frac{{C_\mu}^{3/4} {k_{in}}^{3/2}}{\kappa z}$

Stable atmospheric conditions: Inlet vertical profiles of meteorological variables (WRF)





During these hours, $T_{buildings} > T_{air}$

Including surface heat fluxes of buildings

No surface heat fluxes of buildings

Surface heat fluxes at buildings

- At night, the heat fluxes from buildings is difficult to obtain by the CFD model

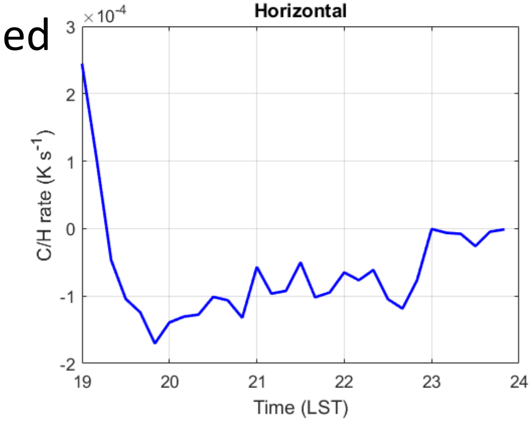
  → Approximation from WRF with the urban parametrization

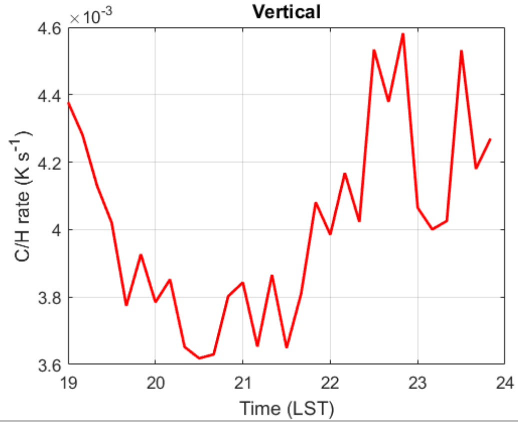
- Assuming in the CFD simulation, the same vertical cooling/heating rate $(\partial\theta/\partial t)$ at each level (every 5 m) obtained over time from mesoscale in the study area.

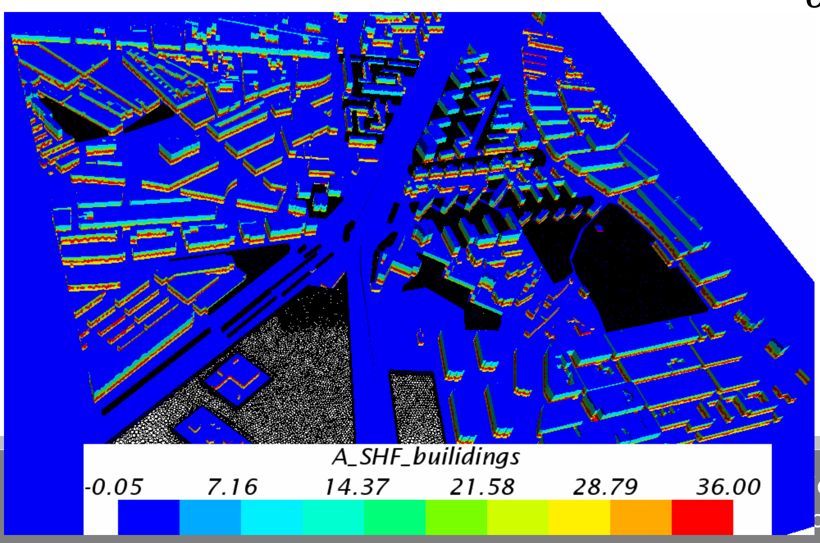
- The surface heat fluxes are computed depending on the detailed area of roofs and walls in the CFD domain following these expressions:

$$H_{s,horz}\Big)_{\Delta z} = \rho\, C_p \frac{\partial\theta}{\partial t}\Big)_{\mathrm{WRF},\Delta z} \frac{V_{air,CFD}}{S_{h,CFD}}\Big)_{\Delta z}$$

$$H_{s,vert}\Big)_{\Delta z} = \rho\, C_p \frac{\partial\theta}{\partial t}\Big)_{\mathrm{WRF},\Delta z} \frac{V_{air,CFD}}{S_{v,CFD}}\Big)_{\Delta z}$$



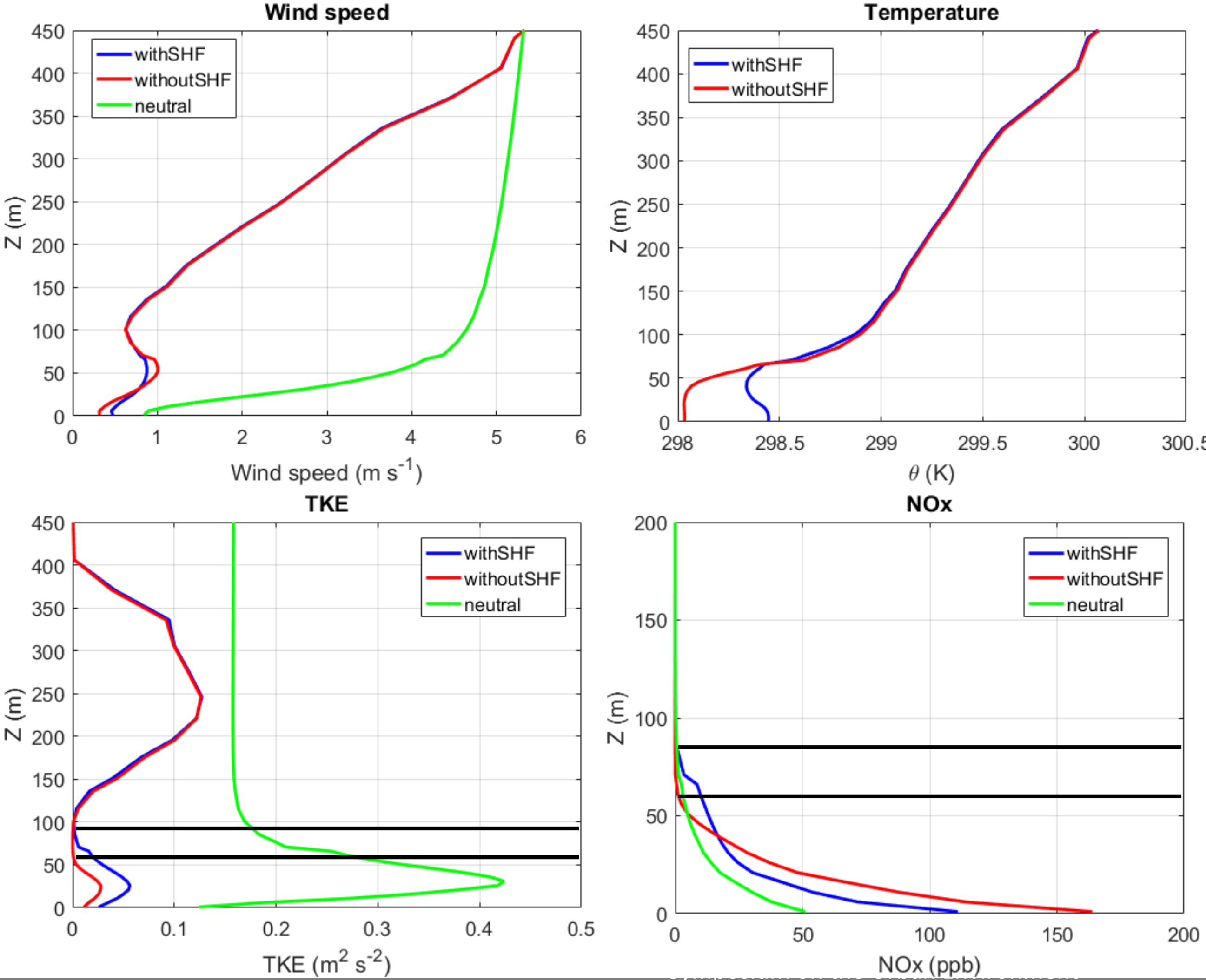




Comparison at 00 LST:

- **Neutral atmospheric conditions** (*neutral*)
- **Inlet mesoscale profiles** *(withoutSHF)*
- **Inlet mesoscale profiles + Surface heat fluxes on buildings** *(withSHF)*

Vertical profiles of the horizontal spatial average over the buildings area of:



Differences in the vertical distribution of wind speed between the neutral assumption and the use of the mesoscale profiles that provides a different behavior of the NO_x concentration in the UCL

Stronger wind speed gives rise to lower concentration at street level

PBL height

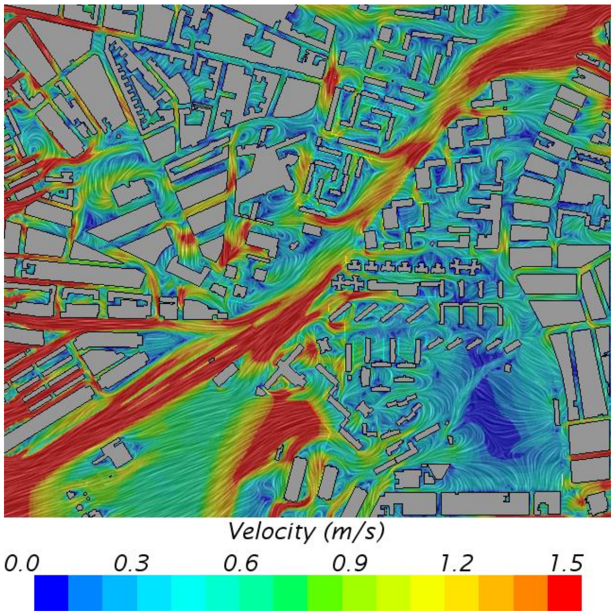
WithoutSHF: h_{PBL}= 60 m

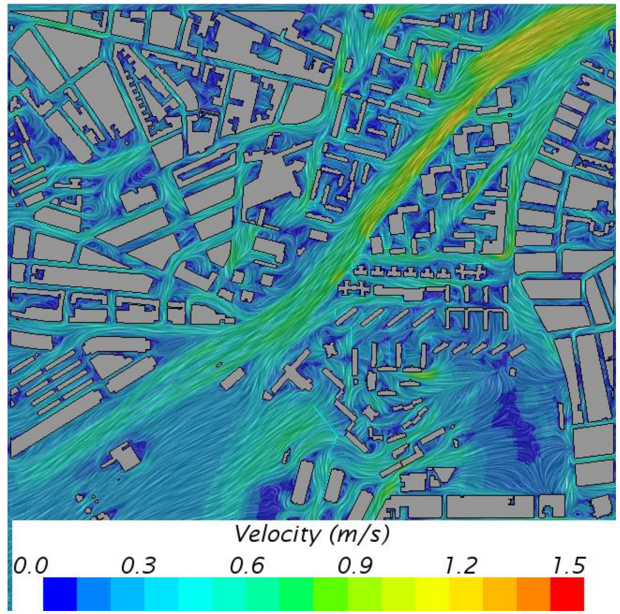
WithSHF: h_{PBL}= 90 m

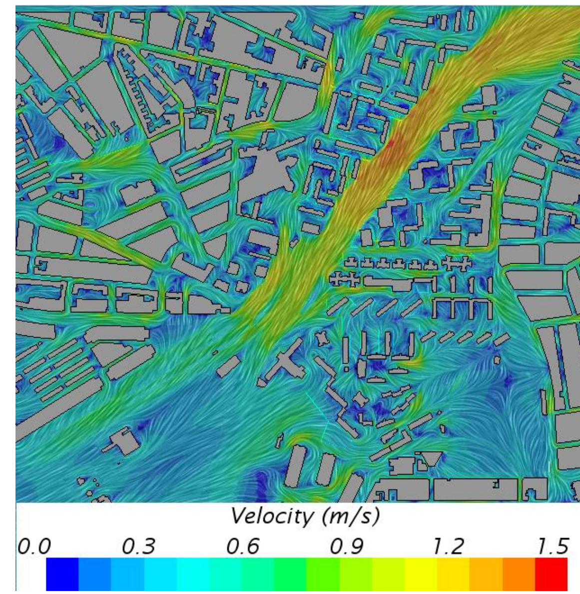
$\delta NO_x)_{SHF}$ = 30% at street level

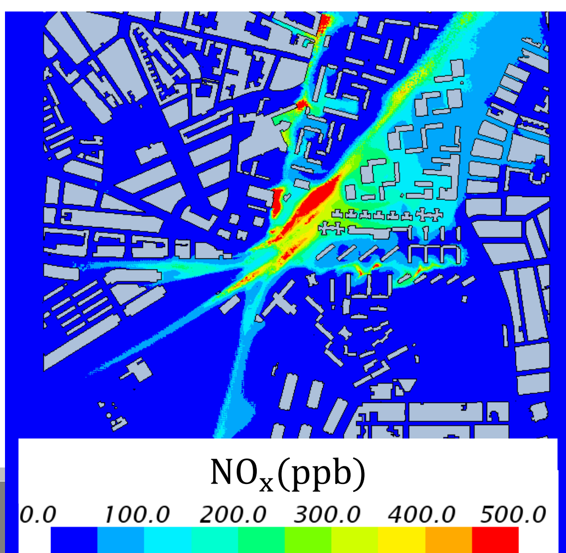
At street level (3 m AGL): Significant differences in the pollutant distribution at street level

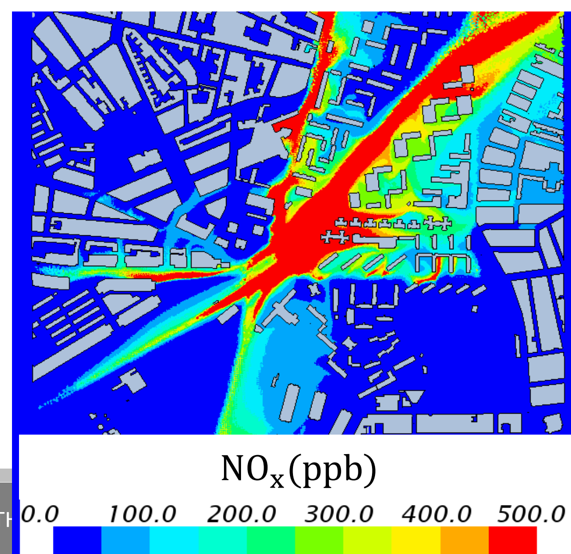
Neutral atmospheric conditions	Inlet mesoscale profiles	Inlet mesoscale profiles + Surface heat fluxes

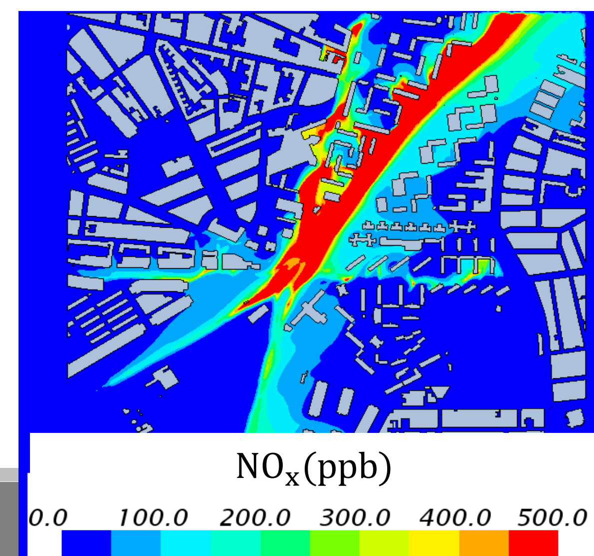












Conclusions

- The importance of adapting the inlet profiles derived from the mesoscale model in the CFD domain, since it affects the flow pattern and the dispersion of pollutants in the research area.
- In stable atmospheric conditions, the use of the mesoscale profiles as input of the CFD simulation allows to reproduce a different vertical behavior of the meteorological variables that cannot be obtained assuming neutral atmospheric conditions.
- At street level, the deviation of the flow pattern modify the spatial distribution of the pollutant concentration.
- The dispersion of pollutant concentration at street level is very sensitive to the use of the surface heat fluxes of buildings and therefore, further studies are necessary to improve the spatial distribution of heat fluxes since the wall temperature changes depending on the building orientation.

Future work

- The evaluation of meteorological variables and concentration of pollutants with experimental data in order to select the most appropriate scenario for the simulation of stable atmospheric conditions using a CFD model.
- The inclusion of **chemical reactions** into the CFD simulation: the NO_2 levels

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Thank you