Microscale Modeling of Effects of Realistic Surface Heat Fluxes on Pollutant Distribution within a Simplified Urban Configuration

J. L. Santiago¹, B. Sanchez and A. Martilli¹

¹ Atmospheric Pollution Division, Environmental Department, CIEMAT, Spain.
Introduction

- Micrometeorology and pollutant dispersion within cities are important for urban climate, air quality and pedestrian comfort.

- Interaction between the atmosphere and urban surfaces:
  - Complex flow patterns within the urban canopy
  - Heterogeneous distributions of temperature and pollutant concentration.
Introduction

- One important physical process: Interaction between heat fluxes from building surfaces and streets and the airflow.

- Thermal effects on flow within the canyon are not taken into account by the majority of microscale studies.

- Most scenarios studied (including thermal effects) to date have only heated one wall of the canyon, or the ground.
Objective

The main objective is to determine the impact of ‘realistic’ distribution of urban surface heat fluxes corresponding to different solar positions on airflow properties and pollutant concentration for a range of ratios of buoyancy to dynamical forces.
**Configuration and Set-up**

- Realistic Distributions Heat Fluxes (TUF model)
- Solar Positions
- Boundary Conditions at walls
- CFD simulation
- Microscale results (flow, concentration)
- Average results (flow, concentration)
**Configuration and Set-up**

- Array of cubes: \( \lambda = 0.25 \)

- 7 solar positions. For each solar position different intensities of heat fluxes are studied.

- Realistic distribution of sensible heat fluxes for each scenario is introduced with high resolution in CFD simulations.
**Configuration and Set-up**

**Boundary conditions for ground and building walls: Microscale 3-D urban energy balance model**

- Temperatures of Urban Facets in 3-D (TUF3D) calculates radiative exchange and surface temperature at the patch/sub-facet scale in 3-D.
- The model assumes radiation is the primary driver of the surface temperature distribution.
- TUF3D compares well with surface temperature measurements from Vancouver and Basel.
- Heat Fluxes obtained with TUF3D are used by CFD model.

Configuration and Set-up

- Microscale (CFD) simulation: RANS model with $k-\varepsilon$ turbulent closure. Transport equation for passive tracer.

- Mesh: Resolution: $h/16$ with prism layer close to building walls and ground.

- Emissions: bottom part of canopy (traffic)

- Top Boundary Conditions:
  - a downward flux of momentum $\rho u_\tau^2$ in the X-momentum equation is imposed to maintain the flow.
  - Concerning temperature boundary conditions at the top, a $T_{ref}$ is fixed allowing a flux equals to
    
    $k_{eff} \left( T_{ref} - T \right) / \Delta z$

    where $keff$ is the effective thermal conductivity.
  
  - Constant concentration
Cases studied

- 7 solar positions. For each solar position different intensities of heat fluxes are studied.
Cases studied

- For each solar position different heat flux intensity. \((h/L_{urb})\). Analogy with Monin-Obukhov length.

\[
L_{urb} = \frac{u_T^3}{\left(\frac{g}{T_{ref}} \frac{Q_h}{\rho C_p}\right)}
\]

- \(h/L_{urb} = 0, 0.4, 0.75, 1.13, 1.5, 2.25, 3\)

- Two simulations with the same \(h/L_{urb}\) and the same solar position provides equivalent results (checked)
Microscale properties (Normalized Temperature)

\[ L_{urb} = \frac{u_\tau^3}{\left(\frac{g}{T_{ref}} - \frac{Q_h}{\rho C_p}\right)} \]

\[ \Delta T_{norm} = \frac{\Delta T}{Q_h/\rho C_p} \frac{\rho C_p}{u_\tau} \]

\[ \Delta T_{norm} \]

\[ h/L_{urb} = 0.4 \]

\[ h/L_{urb} = 0 \]
Microscale properties (Normalized Concentration)

\[ T_{urb} = \left( \frac{g}{T_{ref} \rho C_p} \right) \frac{Q_h}{Q_c} \]
\[ C_{\text{norm}} = C \cdot u_z \cdot h^2 \]

- \( h/L_{urb} = 0.4 \)
- \( h/L_{urb} = 0 \)

Angles:
- 60°
- 45°
- 30°
- 0°
Microscale properties (Temperature normalized)

\[ L_{urb} = \frac{u_\tau^3}{\left( \frac{g}{T_{ref}} \frac{Q_h}{\rho C_p} \right)} \]

\[ \Delta T_{norm} = \frac{\Delta T}{Q_h / \rho C_p \frac{u_\tau}{u_\tau}} \]

\[ h/L_{urb} = 1.5 \]

\[ h/L_{urb} = 0 \]
Microscale properties (Normalized Concentration)

\[
L_{urb} = \frac{u_r^3}{g \frac{Q_h}{T_{ref} \rho C_p}} \\
C_{norm} = \frac{C \cdot u_r \cdot h^2}{Q_c}
\]

\[
\frac{h}{L_{urb}} = 1.5
\]

\[
\frac{h}{L_{urb}} = 0
\]
Microscale properties (Temperature normalized)

\[ \frac{h}{L_{urb}} = 2.25 \]

\[ 60^\circ \]

\[ 45^\circ \]

\[ 30^\circ \]

\[ 60^\circ \]

\[ 45^\circ \]

\[ 30^\circ \]

\[ 0^\circ \]

\[ \frac{h}{L_{urb}} = 0 \]

\[ L_{urb} = \frac{u_\tau^3}{\left( \frac{g}{T_{ref}} \frac{Q_h}{Q_h + \rho C_p} \right) \Delta T_{norm}} = \frac{\Delta T}{Q_h / \rho C_p} \]

\[ u_\tau = \frac{\Delta T_{norm}}{g T_{ref} \rho C_p} \]
Microscale properties (Normalized Concentration)

\[
\frac{h}{L_{urb}} = 2.25
\]

\[
L_{urb} = \frac{u_t^3}{\left( g \frac{Q_h}{T_{ref}} \rho C_p \right)} \quad \text{C}_{\text{norm}} = \frac{C \cdot u_t \cdot h^2}{Q_c}
\]

\[
0^\circ \quad 30^\circ \quad 45^\circ \quad 60^\circ
\]

\[
0 \quad 1.8 \quad 3.6 \quad \text{C}_{\text{norm}} \quad 5.4 \quad 7.2 \quad 9.0
\]
Spatially average flow properties

- CFD → High resolution information → Numerical domain cannot cover the whole city

- Mesoscale models → Urban Canopy Models (compromise between simplicity and accuracy) to parameterize processes at smaller scale than mesoscale resolution (i.e. parametrization of drag forces induced by buildings).
Spatially average flow properties

- Flow

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**Images:**

- Panels a, b, c: Flow properties at different times and zenith angles.
- Panels d, e, f: Flow properties at different times and zenith angles.
- Panels g: Flow properties at different times and zenith angles.

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**Legend:**

- $H/L_{urb} = 0$
- $H/L_{urb} = 0.4$
- $H/L_{urb} = 0.75$
- $H/L_{urb} = 1.13$
- $H/L_{urb} = 1.5$
- $H/L_{urb} = 2.25$
- $H/L_{urb} = 3$

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**Times and Zenith Angles:**

- 0800 (zenith angle = 60°)
- 0900 (zenith angle = 45°)
- 1000 (zenith angle = 30°)
- 1200 (zenith angle = 0°)
- 1400 (zenith angle = 30°)
- 1500 (zenith angle = 45°)
- 1600 (zenith angle = 60°)
Spatially average flow properties

- Normalized Temperature

Note: In the normalization $\Delta T$ is divided by $Q_h$. 

$$\Delta T_{\text{norm}} = \frac{\Delta T}{Q_h/\rho C_p u_\tau}$$
Spatially average flow properties

Normalized Concentration

\[ \frac{C_{\text{norm}}}{C} = \frac{Q}{\tau h^2} \]

- \( H/L_{\text{urb}} = 0 \)
- \( H/L_{\text{urb}} = 0.4 \)
- \( H/L_{\text{urb}} = 0.75 \)
- \( H/L_{\text{urb}} = 1.13 \)
- \( H/L_{\text{urb}} = 1.5 \)
- \( H/L_{\text{urb}} = 2.25 \)
- \( H/L_{\text{urb}} = 3 \)
Spatially average flow properties

- Drag Coefficient (Urban canopy model)

\[ \text{Drag}(z) = -\rho S(z)C_d \cdot U \cdot \hat{U} \]

- \( S(z) \) is the vertical surface building density (facing the wind), \( C_d \) is drag coefficient.

\[ C_{deq} = \frac{\int_0^H \Delta P dz}{\rho \int_0^H U^2 dz} \]

- Drag force integrated in the whole canopy is equal to that computed by RANS simulations.
Spatially average flow properties

- Average concentration at 2.5 m
Summary and Conclusions

- Scenarios with **realistic distributions of heat fluxes** imposed at urban surfaces are simulated by a CFD model analyzing microscale and spatial average properties of the flow and concentration.

- Different solar positions and different intensities of ratios between buoyancy and dynamical forces (variation of $h/L_{urb}$) for each position are simulated.

- For higher $h/L_{urb}$, cases with leeward shaded have higher average concentration close to ground than cases with the other wall heated. This is observed for $h/L_{urb} > 1.0$

- $C_{deq}$ increases substantially (high buoyancy force: $h/L_{urb} > 1.0$) → this effect should be important to include in parameterization of drag in UCP

\[
L_{urb} = \frac{u^3_r}{\left(\frac{g}{T_{ref}} \frac{Q_h}{\rho C_p} \right)}
\]
Thank you for your attention