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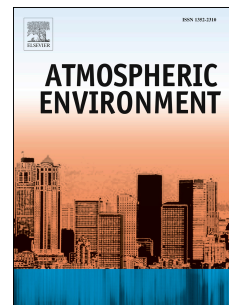
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Lattice-Boltzmann Large-Eddy Simulation of pollutant dispersion in street canyons including tree planting effects

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Abstract

This study assesses the performance of a large eddy simulation (LES) based on the lattice Boltzmann method (LBM) in predicting near field dispersion in street canyons with tree planting. Based on a benchmark test case benefiting from wind tunnel measurements (CODASC), this study qualitatively and quantitatively discusses the prediction of traffic-induced pollutant concentration with respect to several reference studies. It also analyses the physics of the flow and concentration fields. Although the problem might seem rather simple, the flow is highlighted to be strongly three dimensional and transient. These properties enhance pollutant dispersion in the empty street canyon but air flow velocity and turbulence intensity tend to decrease in tree crowns. This effect of trees increases both mean and peak concentration levels at pedestrian level, which may be problematic in cities with dense traffic. These results show that LBM-LES is particularly well suited to study dispersion problems towards the development of more breathable cities.

Keywords: Computational Fluid Dynamics, Lattice Boltzmann Method,

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Large Eddy Simulation, Urban pollutant dispersion, 3D Street canyon, Tree crowns.

1 **1. Introduction**

2 In the current context of environmental stress, near-field pollutant disper-
3 sion issues due to anthropogenic activities are of major concern. According to
4 the World Health Organization's urban ambient air pollution database, more
5 than 80% of people living in cities, for which monitored data are available,
6 face pollution concentration levels that exceed recommendations. This is es-
7 pecially the case in low-income regions (World Health Organization, 2016).
8 A large part of pollutant emission in urban areas is due to transport. Ve-
9 hicles emit 30% of particle material in European cities. This ratio reaches
10 50% in the OECD countries, especially because of diesel use. This pollution
11 substantially increases risks of diseases and prematured death rates in cities
12 (World Health Organization, 2018). Hence, while greenery is currently pro-
13 moted as a solution to improve urban environmental quality including urban
14 micro-climates and air quality thanks to filtering and deposition on plant
15 foils, the inverse effect of trees on pollutant dispersion in dense cities with
16 street canyons may be problematic (Gromke and Ruck, 2007, 2009; Janhäll,
17 2015; Abhijith and Gokhale, 2015; Abhijith et al., 2017; Jeanjean et al., 2017;
18 Santiago et al., 2017; Xue and Li, 2017): tree crowns also tend to curb airflow
19 and reduce the natural ventilation potential of streets, thus increasing pedes-
20 trian exposure to high levels of pollutant concentration. Wise urban planning
21 choices should consequently be made to improve the breathability of urban
22 areas in a context of climate change. However, in urban environments that

23 include sharp-edged buildings and trees, air flows and pollutant dispersion
24 processes are complex (Britter and Hanna, 2003; Ahmad et al., 2005; Lateb
25 et al., 2016), making predictions and thus decisions more difficult.

26 Hence, for several decades now, different approaches to study urban flow
27 and dispersion issues were developed. Thanks to the recent progress in com-
28 putational capabilities, the use of detailed numerical approaches - typically
29 computational fluid dynamics (CFD) - has increased, improving the accuracy
30 of predictions. Capable of providing whole flow field data, this investigation
31 technique advantageously completes experimental approaches and systematic
32 field measurements. Although requiring an appropriate use and implemen-
33 tation, CFD is especially beneficial to highlight basic aerodynamic mecha-
34 nisms underlying dispersion and to study virtual scenarios (Vardoulakis et al.,
35 2003; Moonen et al., 2012; Tominaga and Stathopoulos, 2013; Blocken, 2015;
36 Lateb et al., 2016). In urban physics, most studies rely on steady statistically
37 averaged methods (Reynolds Averaged Navier–Stokes - RANS), because of
38 the smaller computational costs involved. However, the accuracy of usual
39 steady RANS approaches for studying dispersion in built environments is of-
40 ten found rough because of their inherent limitation in solving transient pro-
41 cesses and turbulent transfers, which are important for dispersion (Tominaga
42 and Stathopoulos, 2011; Salim and Ong, 2013; Tominaga and Stathopoulos,
43 2016). The use of time dependent approaches that resolve large scales of
44 turbulence - typically large eddy simulation (LES) - appears therefore effec-
45 tive, but this also raises additional modeling challenges compared to RANS
46 (Blocken, 2014, 2015). Especially, suitable boundary conditions should be
47 specified (Tabor and Baba-Ahmadi, 2010), and the efficiency of the solver

48 used is critical due to the increased computational costs LES involves in
49 comparison to RANS.

50 The development and use of effective simulation approaches such as Lat-
51 tice Boltzmann Method (LBM (Chen and Doolen, 1998; Succi, 2001; Shan
52 et al., 2006; Guo and Shu, 2013; Krüger et al., 2017))-based LES approaches
53 appear thus promising for urban applications. Indeed, thanks to its lo-
54 cal and explicit formulation compared to Navier-Stokes-based approaches,
55 this method is inherently parallel and very efficient to simulate low Mach
56 separated flows. Regarding urban applications, first uses of this method
57 addressed the simulation and visualization of contaminant dispersion using
58 GPU (Graphics Processing Unit) for civil security (Fan et al., 2004; Qiu et al.,
59 2004). Ten years later, this approach is receiving more and more interest be-
60 cause of its efficiency, although being still an emergent method. Contempo-
61 rary studies especially address its accuracy and computational performance
62 when implemented on GPUs (Obrecht et al., 2015; King et al., 2017), take
63 advantage of this massively parallelizable method to discuss the link between
64 urban morphology and pedestrian comfort (Ahmad et al., 2017; Jacob and
65 Sagaut, 2018), or to quantify uncertainties or assimilate data for pollutant
66 dispersion (Margheri and Sagaut, 2016; Mons et al., 2017).

67 To examine further the applicability and performance of LBM LES for
68 urban issues, the present paper discusses qualitatively and quantitatively the
69 accuracy of such an approach to address dispersion problems in the urban
70 canopy layer. More specifically, the present study discusses results of LBM
71 LES performed using ProLB (CS, 2018; M2P2, 2018) with respect to a bench-
72 mark test case: the COncentration DAta of Street Canyons - CODASC (KIT,

73 2017). The CODASC focuses on pollutant dispersion in a street canyon with
 74 traffic-like pollutant emissions for different configurations of avenue-like tree
 75 planting. This configuration is used to analyze the physical processes that
 76 underlay dispersion in the urban canopy layer, as made possible by high
 77 fidelity modeling approaches.

78 The present paper is organized as follows. First, Sec. 2 presents the key
 79 features of the LBM LES approach used for this study. Second, Sec. 3 is
 80 dedicated to the CODASC benchmark in terms of experiment (Sec. 3.1) and
 81 related numerical studies (Sec. 3.2). Then Sec. 4 discusses the modeling we
 82 developed using ProLB (Sec. 4.1). It also presents the grid sensitivity analy-
 83 sis results (Sec. 4.2) and qualitatively and quantitatively discusses simulation
 84 results with respect to experimental data (Sec. 4.3). On this basis, Sec. 5
 85 analyses the physics of the flow and the associated turbulent dispersion pro-
 86 cesses. Finally, Sec. 6 synthesizes the main results of this study and gives
 87 outlooks.

88 **2. The hybrid LBM LES approach**

89 *General approach.* The Boltzmann equation is a statistical equation, which
 90 describes the evolution of the distribution function f of a particle of mass m
 91 and speed ξ undergoing an external force \mathbf{F} in a fluid:

$$\frac{\partial f}{\partial t} + \xi \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \xi} = \Omega(f) \quad (1)$$

92 where $\Omega(f)$ is a collision operator standing for particle interactions during
 93 shocks.

94 Based on a mesoscopic description, the LBM aims at simulating the fluid
 95 behavior by resolving a discretized version of the Boltzmann equation in
 96 phase space, using (CS, 2016):

- 97 1. a discrete velocity model $c_{\alpha, \alpha=0 \dots Q-1}$ in a space of dimension D . A
 98 D3Q19 scheme is typically used for 3D problems;
- 99 2. a collision model towards relaxation. The simplest model is the single
 100 relaxation time Bhatnagar-Gross-Krook (BGK) model:

$$\Omega = -\frac{1}{\tau} (f - f^{eq}) \quad (2)$$

101 with: $\left\{ \begin{array}{l} \tau: \text{the relaxation time,} \\ f^{eq}: \text{the equilibrium function;} \end{array} \right.$
 102

- 103 3. and an equilibrium function model. This function generally corre-
 104 sponds to the development of the Maxwell-Boltzmann distribution func-
 105 tion.

106 After projection and integration of Eq. 1, and neglecting at first external
 107 forces, the LBM BGK formulation reads:

$$f_{\alpha}(\mathbf{x} + \mathbf{c}_{\alpha} \Delta t, t + \Delta t) - f_{\alpha}(\mathbf{x}, t) = -\frac{\Delta t}{\tau} (f_{\alpha}(\mathbf{x}, t) - f_{\alpha}^{eq}(\mathbf{x}, t)) \quad (3)$$

108 The left hand side of Eq. 3 corresponds to the stream phase and the right
 109 hand side of Eq. 3 corresponds to the collision phase. The development of
 110 the equilibrium function to the second order is given by :

$$f_{\alpha}^{eq}(\mathbf{x}, t) = \rho \omega_{\alpha} \left(1 + \frac{c_{\alpha i} u_i}{c_s^2} + \frac{1}{2c_s^4} Q_{\alpha ij} u_i u_j \right) \quad (4)$$

111 with: $\begin{cases} \omega_\alpha \text{ and } c_s: \text{ weight and sound velocity constants depending on the lattice used,} \\ 112 Q_{\alpha ij} = c_{\alpha i} c_{\alpha j} - c_s^2 \delta_{ij}. \end{cases}$

113 From LBM, usual macroscopic quantities such as the fluid density ρ and
114 flow momentum $\rho \mathbf{u}$ can be recovered as follows:

$$\rho = \sum_{\alpha} f_{\alpha}; \quad \rho \mathbf{u} = \sum_{\alpha} f_{\alpha} \mathbf{c}_{\alpha} \quad (5)$$

115 Also, with the the BGK collision operator, the kinematic viscosity ν is
116 related to the relaxation time τ , following:

$$\nu = c_s^2 \left(\tau - \frac{\Delta t}{2} \right) \quad (6)$$

117 This general LBM framework model allows to recover the Navier–Stokes
118 equation to the second order and is the basis of the CFD solver ProLB. Nev-
119 ertheless, in order to enhance the stability of computation while keeping the
120 simplicity and accuracy of the scheme, a third-order expansion of the equilib-
121 rium function was used in the present study, along with a hybrid Recursive
122 Reconstruction procedure for the non-equilibrium part of the distribution
123 function $f_{\alpha}^{neq} = f_{\alpha} - f_{\alpha}^{eq}$ (see Jacob et al. (2018) for details). Using the
124 Chapman Enskog expansion, it is possible to show that :

$$f_{\alpha}^{neq} \approx \underbrace{\frac{Q_{\alpha ij}}{2c_s^4} \sum_{\alpha} c_{\alpha i} c_{\alpha j} (f_{\alpha} - f_{\alpha}^{eq})}_{f_{\alpha}^{neq,LBM}} = \underbrace{-\frac{\tau \omega_{\alpha}}{2c_s^2} Q_{\alpha ij} \left(\frac{\partial \rho u_j}{\partial x_i} + \frac{\partial \rho u_i}{\partial x_j} \right)}_{f_{\alpha}^{neq,DF}} \quad (7)$$

125 According to Eq. 7, f_{α}^{neq} could be estimated using the local distribution
126 functions ($f_{\alpha}^{neq,LBM}$) or the derivatives of the macroscopic values ($f_{\alpha}^{neq,DF}$),
127 which may be evaluated using second order finite differences. Hence, in order

128 to enhance stability while limiting numerical dissipation, f^{neq} is computed
 129 in our model as follows:

$$f_{\alpha}^{neq} = \sigma f_{\alpha}^{neq,LBM} + (1 - \sigma) f_{\alpha}^{neq,DF} \quad (8)$$

130 with $\sigma \in [0; 1]$.

131 *Treatment of external forces.* In order to take source terms (\tilde{S}) into account,
 132 the right hand side of Eq. 3 can be modified as follows:

$$f_{\alpha}(\mathbf{x} + \mathbf{c}_{\alpha}\Delta t, t + \Delta t) - f_{\alpha}(\mathbf{x}, t) = -\frac{\Delta t}{\tau}(f_{\alpha} - f_{\alpha}^{eq}) + S_{\alpha}(\mathbf{x}, t) \quad (9)$$

133 According to Guo et al. (2002), the following development of an external
 134 force (\mathbf{S} non-dimensionalized following $\mathbf{S} = \tilde{\mathbf{S}} \frac{\Delta t^2}{\Delta x}$) can be more particularly
 135 considered in order to accurately recover the Navier–Stokes equations :

$$\mathbf{S}_{\alpha}(\mathbf{x}, t) = \rho \left(1 - \frac{1}{2\tau}\right) \omega_{\alpha} \left[\frac{\mathbf{c}_{\alpha} - \mathbf{u}}{c_s^2} + \frac{\mathbf{c}_{\alpha}(\mathbf{c}_{\alpha} \cdot \mathbf{u})}{c_s^4} \right] \cdot \mathbf{S} \quad (10)$$

136 The macroscopic velocity is then given by:

$$\mathbf{u}(\mathbf{x}, t) = \frac{1}{\rho} \sum_{\alpha} \mathbf{c}_{\alpha} f_{\alpha}(\mathbf{x}, t) + \frac{\Delta t}{2\rho} \mathbf{S} \quad (11)$$

137 In the present study, the aerodynamic drag of trees is taken into account
 138 by introducing a volumic Forchheimer force (F_{por} [N m^{-3}]) designed to ac-
 139 count for porous media effects on turbulent flows:

$$F_{por} = -\rho \times R \times |\mathbf{u}| \times \mathbf{u} \times \Phi \quad (12)$$

140 with: $\left\{ \begin{array}{l} R : \text{the drag force coefficient } [\text{m}^{-1}], \\ \Phi : \text{the ratio of porous media immersed in the volumic cell.} \end{array} \right.$
 141

142 *Hybrid approach.* To solve the conservation equations for species (passive
143 scalar) while remaining within the LBM framework, it is possible to use a
144 multidistribution approach. Multidistribution means that an additional su-
145 perimposed lattice is considered to solve passive scalar transport. Nonethe-
146 less, given the correspondence between the LBM and Navier–Stokes ap-
147 proaches, it is also possible to develop a hybrid approach to solve passive
148 scalar transport when basically using the LBM. In such an approach, the mass
149 and momentum conservation equations are solved using the LBM while the
150 species conservation equations are solved using a usual finite volume / finite
151 difference method. This method allows thus to consider only one additional
152 unknown per additional equation. Typically, in ProLB, the species conser-
153 vation equation is solved using a finite difference vertex centered scheme. A
154 centered scheme using the 18 neighbors defined in the LBM lattice mixed
155 with a first order upwind scheme is used for the advective term whereas a
156 standard centered second order scheme is used for diffusion term.

157 *Boundary conditions.* As most of LBM solvers, ProLB uses the immersed
158 boundary method to include solid boundaries. This method decouples the
159 triangular surfacic mesh from the cubic volumic mesh. As each near wall node
160 do not have all its neighbors in the fluid domain, the lattice Boltzmann algo-
161 rithm cannot be applied. For these particular nodes, macroscopic quantities
162 are computed using an interpolation (Dirichlet condition) or an extrapola-
163 tion (Neumann condition) between the fluid and the solid boundary, or wall
164 functions. The distribution functions are then reconstructed from equations
165 (4) and (7). This method substantially reduces meshing costs compared to
166 usual unstructured meshes based on surface discretization.

167 *Large eddy simulation.* The LBM is inherently well suited to dynamically
 168 solve flows using the LES technique. With LES, the most energy carrying
 169 and problem dependent eddies are solved. Conversely, eddies smaller than
 170 the spatial filter -typically the grid mesh- are modeled. For this purpose,
 171 the Smagorinsky (Smagorinsky, 1963) subgrid viscosity model is commonly
 172 used:

$$\nu_t = (C\Delta)^2 |S| \quad (13)$$

173 with: $\left\{ \begin{array}{l} \nu_t : \text{the subgrid scale eddy viscosity,} \\ \Delta : \text{the width of the filter, taken equal to the mesh size in the present study,} \\ C : \text{the Smagorinsky constant, taken equal to 0.18 in the present study,} \\ |S| = (2S_{ij}S_{ij})^{1/2} : \text{the magnitude of the resolved strain rate tensor.} \end{array} \right.$
 174

175 In ProLB, the subgrid scale viscosity is added to the molecular viscosity
 176 of Eq. 6 to perform LES.

177 3. The CODASC benchmark

178 3.1. Wind tunnel setup and results

179 [Figure 1 about here.]

180 The CODASC database (KIT, 2017; Gromke et al., 2008; Gromke and
 181 Ruck, 2009, 2012) provides detailed reduced-scale measurements of traffic-like
 182 induced pollutant concentration next to the walls of a street canyon model.
 183 The CODASC deals with different configurations, including different aspect
 184 ratios (H/W), wind incidences and artificial tree plantings. The present study

185 focuses on the $H/W = 1$ configuration with a wind direction perpendicular
 186 to the street canyon axis with and without continuous tree planting.

187 Reference experiments were carried out in a boundary layer wind tunnel
 188 with smooth walls and ceiling. This ceiling was adjusted in order to obtain a
 189 zero pressure gradient in the streamwise direction. The cross section is 2 m
 190 large (Y direction) and 1 m high (Z direction).

191 According to Figure 1(b), small solid elements on the floor were used as
 192 roughness to reproduce a typical urban boundary layer mean velocity pro-
 193 file. A 0.3 power law profile for the mean velocity of the boundary layer
 194 was achieved. Considering $U_H = 4.65 \text{ m s}^{-1}$ at the building height (H),
 195 the Reynolds number of the test equals 3.7×10^4 , so the flow is turbulent.
 196 The measured turbulence intensities are characterized by a decreasing -0.36
 197 power law profile with height.

198 As shown in Figures 1(a) and 1(b), the street canyon model consists of
 199 two $H = 0.12 \text{ m}$ high, $L=10 H$ long rectangular obstacles made of contiguous
 200 blocks of plexiglas. When present, tree crowns were modeled with rectangular
 201 volumes made of a fiber like wading material enclosed in suspended metal-
 202 lic lattice cages (Gromke and Ruck, 2009). Trunks were neglected. Different
 203 tree crowns types were realized by varying the mass of wading material in the
 204 lattice cage. Corresponding porosity properties were experimentally deter-
 205 mined and characterized with a normalized pressure loss coefficient ($\lambda [\text{m}^{-1}]$),
 206 as follows:

$$\lambda = \frac{p_{ww} - p_{lw}}{(\frac{1}{2}\rho u^2)d} \quad (14)$$

$$\begin{array}{l}
207 \text{ with: } \left\{ \begin{array}{l}
p_{ww} : \text{the windward pressure [Pa]}, \\
p_{lw} : \text{the leeward pressure [Pa]}, \\
\rho : \text{the fluid density [kg m}^{-3}\text{]}, \\
u : \text{the mean streamwise velocity [m s}^{-1}\text{]}, \\
d : \text{the streamwise thickness of the wadding material [m]}.
\end{array} \right.
\end{array}$$

208
209 The CODASC database reports measurements for $\lambda = 0 \text{ m}^{-1}$ (no tree),
210 $\lambda = 80 \text{ m}^{-1}$ and $\lambda = 200 \text{ m}^{-1}$.

211 The traffic-like pollutant release was modeled using four line sources of
212 equal strength located on the street canyon ground. These sources are more
213 precisely composed of equidistant little openings with high pressure drop
214 to ensure that the release remains unaffected by local pressure fluctuation
215 induced by the street canyon flow. Emissions consisted of a mixture of sulfure
216 hexafluoride (SF6, $Q_{SF6} = 6.5 \text{ cm}^3 \text{ min}^{-1}$, tracer gas) and dry air ($Q_{air} =$
217 $7 \times 10^3 \text{ cm}^3 \text{ min}^{-1}$). Mean tracer gas concentrations were measured at $x^+ =$
218 $0.04167 \frac{x}{H}$ from street canyon building walls using electron capture detectors.
219 The 700 molar concentration measures (c_{mol}) distributed over the 7 horizontal
220 lines available for each wall were normalized as follows:

$$c^+ = \frac{C_{mol} H U_H}{Q_l} \quad (15)$$

$$\begin{array}{l}
221 \text{ with: } \left\{ \begin{array}{l}
c^+ : \text{the normalized concentration [-]} \\
H : \text{the building height [m]} \\
U_H : \text{the wind velocity at H [m s}^{-1}\text{]} \\
Q_l : \text{the emission rate of the line source [m}^2 \text{s}^{-1}\text{]}
\end{array} \right.
\end{array}$$

223 Experimental measures available in the database were symmeterized. Ex-
224 perimental results show weaker concentration levels on the windward wall
225 (wall B) than on the leeward wall (wall A). This distribution is explained
226 by the formation of a street canyon vortex, which is driven by the above
227 flow (Gromke and Ruck, 2009). The canyon vortex drives pollutant from the
228 street canyon ground towards wall A, and upwards. Part of pollution is then
229 mixed with the above flow at roof level. The other part is re-entrained in
230 a new cycle of the canyon vortex, which explains the presence of pollutant
231 next to wall B. In addition, corner eddies enhance ventilation in the canyon
232 after separation at the lateral edges of block A, which decreases pollution at
233 street canyon ends. In the absence of trees, these typical flow structures of
234 3D street canyons induce an averaged concentration level on wall A that is
235 3.8 times higher than on wall B.

236 The presence of trees reduces exchanges between the street canyon and
237 the ambient flow. Corner eddies are blocked at the street canyon ends, and
238 the canyon vortex is highlighted weaker in the central part of the street than
239 in the empty street canyon. Velocity is substantially reduced next to wall
240 B. Velocity next to wall A is also reduced. These modifications induce a
241 substantial increase of pollutant concentration levels next to wall A, as well
242 as a decrease of pollutant concentration at wall B. As explained in Gromke
243 et al. (2008), the rotating fluid mass decreases when trees are located in the
244 street, leading to a reduction of the pollutant mass ejected above wall A
245 to wall B and a decrease of pollutant concentration close to wall B. Thus,
246 higher concentrations are observed in the street canyon with tree planting
247 than in the empty street canyon: the total pollutant increase is about 28 % for

248 $\lambda = 80 \text{ m}^{-1}$ and 36 % for $\lambda = 200 \text{ m}^{-1}$. Additional experiments highlighted
249 no substantial change in wall-averaged pollution concentrations for higher
250 values of λ .

251 3.2. Related studies

252 The CODASC benchmark was considered by several studies to assess the
253 performance of different CFD approaches in predicting pollutant dispersion
254 in the presence of trees. Studies often considered the H/W=1 configuration
255 with a wind incidence perpendicular to the canyon axis (Gromke et al., 2008;
256 Balczó et al., 2009; Salim et al., 2011; Moonen et al., 2013; Gromke and
257 Blocken, 2015a; Vranckx et al., 2015; Kang et al., 2017), or the H/W=0.5
258 configuration (Buccolieri et al., 2009, 2011; Abhijith and Gokhale, 2015; Xue
259 and Li, 2017). Table 1 gives an overview of the different CFD studies per-
260 formed for the H/W=1 configuration.

261 [Table 1 about here.]

262 Studies referenced in Table 1 generally highlighted that simulation is ca-
263 pable of reproducing the main flow and concentration patterns highlighted
264 in the experiment. However, quantitative analysis generally exhibits discrep-
265 ancies between predictions and measurements. In particular, using steady
266 RANS, the street canyon vortex is generally predicted weaker than observed
267 in the wind tunnel experiments or more detailed approaches (Gromke et al.,
268 2008; Salim et al., 2011; Vranckx et al., 2015). This behavior can be ex-
269 plained by the underprediction of the turbulent kinetic energy at the canyon
270 top, which induces too small shear at the canyon top. Regarding dispersion,
271 studies pointed out the unequal performance of turbulence models (RSM was

272 often found to perform better than $k - \varepsilon$) and the dependence of predicted
273 concentrations with respect to the choice of the turbulent Schmidt number
274 as well as the limitation of steady state approaches in reproducing the mix-
275 ing processes, which are intrinsically transient (Gromke et al., 2008; Salim
276 et al., 2011; Gromke and Blocken, 2015b). These reasons could explain the
277 variable behaviors of RANS results in terms of concentrations on walls A and
278 B in the reviewed studies. Nonetheless, overall, studies generally concluded
279 that RANS approaches may constitute an acceptable compromise between
280 prediction accuracy, applicability and computational costs. Using unsteady
281 RANS, Kang et al. (2017) found also a relatively satisfactory agreement
282 between predictions and measurements in terms of flow and concentration
283 patterns for the different tested tree configurations, but concentrations were
284 underestimated for wall A and overestimated for wall B.

285 When comparing LES to RANS, Salim et al. (2011) found a substantially
286 better performance of LES than that of RANS, especially with respect to the
287 consistency of concentration distributions. The better performance of LES
288 was explained by its ability to reproduce intermittent turbulent fluctuations.
289 LES predictions were found almost satisfactory on wall A, but deviations
290 were still highlighted on wall B (Salim et al., 2011; Moonen et al., 2013).
291 Moreover, Salim et al. (2011) and Moonen et al. (2013) emphasized that
292 LES enables the instantaneous and intermittent behavior of the flow to be
293 analyzed, thus providing information on dispersion processes as well as short
294 term exposure problems.

295 These advantages of LES involve nonetheless significant additional com-
296 putational costs with respect to RANS, which may be limiting for its develop-

297 ment for urban applications. As a matter of fact, Salim et al. (2011) indicates
 298 that performing LES instead of RANS induced an increase of computational
 299 costs of one or two orders of magnitude. Hence, given the addressed problem
 300 and the conclusions of related studies, this benchmark appears well suited to
 301 highlight and discuss the performance of innovative CFD approaches, such
 302 as the present LBM LES.

303 4. Numerical modeling and performance evaluation

304 4.1. Numerical settings

305 To assess the applicability and performance of the LBM LES approach we
 306 developed in ProLB for urban pollution issues, this study focuses on a bad
 307 case for dispersion: the street canyon perpendicular to the wind incidence.
 308 The studied configuration corresponds to the reduced scale (1:150) H/W=1
 309 street canyon, containing, or not, continuous avenue-like tree plantings ($\lambda =$
 310 0, 80 and 200 m⁻¹).

311 [Figure 2 about here.]

312 Figure 2(a) depicts the $L_D \times W_D \times H_D = 3 \times 2 \times 1$ m³ computational
 313 domain set for simulation to reproduce the experimental test section. The
 314 fetch equals 7 H and the inflow was specified with a velocity inlet condition,
 315 as follows (Moonen et al., 2013):

$$\frac{U(y)}{U_H} = \left(\frac{y}{y_H} \right)^{k_u} \quad (16)$$

$$\begin{array}{l}
316 \text{ with:} \\
317 \\
\end{array}
\left\{ \begin{array}{l}
k_u = 0.3 : \text{ the power law exponent,} \\
y_H = H = 0.12 \text{ m} : \text{ the canyon height,} \\
U_H = 4.65 \text{ m s}^{-1} : \text{ the wind velocity at } y=H.
\end{array} \right.$$

318 The Synthetic Eddy Method (Pamiès et al., 2009) was used to provide
319 the turbulent contribution of the approaching flow, based on the following
320 profile of turbulence intensity (Moonen et al., 2013):

$$\frac{I(y)}{I_H} = \left(\frac{y + y_D}{y_H + y_D} \right)^{k_I} \quad (17)$$

$$\begin{array}{l}
321 \text{ with:} \\
322 \\
\end{array}
\left\{ \begin{array}{l}
k_I = -0.65 : \text{ the power law exponent,} \\
I_H = 14.7\% : \text{ the turbulence intensity at reference height,} \\
y_d = -\left(1 + \frac{k_I}{k_u}\right) y_{tke}, \\
y_{tke} = 0.017 \text{ m} : \text{ the vertical position of the center of the shear layer}
\end{array} \right.$$

323 A constant pressure condition was set at the outflow. Lateral and top
324 domain boundaries were specified as frictionless walls and the floor was spec-
325 ified as a 3.3×10^{-3} m high rough floor. The walls of blocks A and B forming
326 the street canyon were assumed smooth (Figure 2(b)). In addition, sponge
327 layers (Xu and Sagaut, 2013) were applied at the top and outlet boundaries
328 (see Figure 2(a)) to absorb waves generated at the initialization of the com-
329 putation. In these layers, the density is progressively relaxed towards its
330 initial value.

331 [Figure 3 about here.]

332 When present, trees were accounted for as simple porous media with

333 aerodynamic drag. They were thus modeled by creating porous zones at
 334 crown location (Figure 3(a)). The pressure loss coefficient ($R [\text{m}^{-1}]$) was
 335 specified using Eq. 12, according to experimental indications depending on
 336 the crown permeability ($\lambda [\text{m}^{-1}]$) following:

$$R = \frac{\lambda}{2} \quad (18)$$

337 [Figure 4 about here.]

338 Figure 4 displays the mesh used for simulation, which includes five nested
 339 refinement zones. Spatial discretization involves $dx = H/96$ lattices in the
 340 canyon. The corresponding basic time step equals 1.44×10^{-5} s in order to
 341 fulfill CFL and low Mach flow requirements. Overall, 4.1×10^7 grid points
 342 are used to mesh the full domain. Simulations were performed on the French
 343 GENCI's Occigen supercomputer using 240 cores and run over 25 s of physical
 344 time.

345 To model pollutant sources, $1.42 \times 1.25 \times 10^{-3} \text{m}^2$ lines sources were created
 346 on the domain bottom boundary (Figure 3(b)) and activated at $t = 8$ s. With
 347 a massic emission concentration of $4.786 \times 10^{-3} \text{kg kg}^{-1}$ and a vertical velocity
 348 equal to 0.2054m s^{-1} , the mass flow rate of SF_6 is $2.094 \times 10^{-6} \text{kg s}^{-1}$. The
 349 corresponding mass flow rate of air is $4.375 \times 10^{-4} \text{kg s}^{-1}$. Diffusivity of
 350 SF_6 was set to $2.3 \times 10^{-5} \text{m}^2 \text{s}^{-1}$ and the subgrid Schmidt number to 0.7.
 351 Although an influence of the turbulent Schmidt number was observed on
 352 previous RANS studies, only one value of the subgrid Schmidt number was
 353 used. Indeed, since a LES model is used the main part of turbulent effects is
 354 resolved and only a small part is modeled, which decreases the importance
 355 of that numerical parameter.

356 According to convergence analysis, the last 10 s of simulation were kept
 357 for post processing and time averaging of results. For physical analysis,
 358 velocities (u_i) were normalized (u_i^+), as follows:

$$u_i^+ = \frac{u_i}{U_H} \quad (19)$$

359 and concentration results (c_m) were normalized following:

$$c^+ = \frac{c_m \times U_H \times H}{Q_{SF6}/l} \times \frac{M_{air}}{M_{SF6}} \quad (20)$$

360 with: $\left\{ \begin{array}{l} c^+ = : \text{the normalized concentration,} \\ H = 0.12 \text{ m} : \text{the height of the street canyon,} \\ l = 1.42 \text{ m} : \text{the length of the line sources,} \\ Q_{SF6} = 1.359 \times 10^{-6} \text{ m}^3 \text{ s}^{-1} : \text{the volumic flow rate of SF6,} \\ M_{air} = 28.966 \text{ g mol}^{-1} : \text{the molar mass of air,} \\ M_{SF6} = 146.055 \text{ g mol}^{-1} : \text{the molar mass of SF6.} \end{array} \right.$

361 4.2. Grid sensitivity analysis

362 In order to analyze the grid influence on the results, the configuration
 363 without trees was tested using the grid defined on Sec. 4.1 and a coarser
 364 grid with $dx = H/48$ in the street canyon. Figure 5 shows the normalized
 365 concentration c^+ profiles in front of wall A and B for the two simulated grids
 366 and the measurements. A better agreement is observed for the finest grid at
 367 wall A, however, there is no significant differences at wall B.

368 [Figure 5 about here.]

369 In order to assess more quantitatively the accuracy of simulation and eval-
370 uate the general model performance as recommended in Chang and Hanna
371 (2004); Hanna and Chang (2012); Moonen et al. (2013), several integrated
372 indicators were also estimated:

- 373 • the fraction of predictions within a factor of two of observation (FAC2)
- 374 • the fractional bias (FB),
- 375 • the root normalized mean square error (RNMSE),
- 376 • the geometric mean bias (MG),
- 377 • the geometric variance (VG),
- 378 • and the correlation coefficient (R).

379 [Table 2 about here.]

380 Their meaning as well as target values and acceptable range for urban
381 problems according to Chang and Hanna (2004) are synthesized in Table 2.
382 The different indicators computed for the two grids are listed in Table 3. All
383 of them are located in the acceptable range for coarse and fine grid which
384 means that the model is consistent with grid refinement. Furthermore most
385 of the quality metrics computed for the finest grid are closer to the target
386 values than the ones computed for the coarse grid. Since the results presented
387 in Figure 5 and Table 3 are slightly better for the finest grid, this grid with
388 $dx = H/96$ in the street canyon was selected for the actual study.

389 [Table 3 about here.]

390 *4.3. Performance evaluation*

391 *Qualitative evaluation.*

392 [Figure 6 about here.]

393 To evaluate the correspondence between predictions and observations,
 394 Figure 6 firstly compares the simulated w^+ field, at $y/H = 0.5$ with LDV
 395 measurements reported in Gromke et al. (2008). Gromke and Ruck (2009)
 396 show that wall averaged c^+ is not very sensitive to λ value for $\lambda \geq 200 \text{ m}^{-1}$,
 397 which means that the flow in the street canyon is quite independent of λ
 398 in that range of values. From this result, Figure 6(b) compares velocity
 399 fields considering $\lambda = 200 \text{ m}^{-1}$ for simulation results and $\lambda = 250 \text{ m}^{-1}$ for
 400 experimental results. Results highlight that predicted and observed velocity
 401 distributions are in good agreement, showing both the development of a
 402 street canyon vortex, and reduced velocities in and around tree crowns when
 403 present, especially next to wall B.

404 [Figure 7 about here.]

405 According to Figure 7, which compares c^+ contours on walls A and B
 406 for the different configurations, reduced velocity tends to increase pollutant
 407 concentration in the central part of the street canyon on wall A and decreases
 408 it on wall B, although it is less obvious on simulation results. More specif-
 409 ically, maximum concentration occurs for the densest tree configuration on
 410 wall A ($c_{max,exp}^+ \approx 60$ and $c_{max,sim}^+ \approx 70$ for $\lambda = 200 \text{ m}^{-1}$ vs. $c_{max,exp}^+ \approx 40$
 411 and $c_{max,sim}^+ \approx 45$ for $\lambda = 0 \text{ m}^{-1}$), and concentration decreases or remains
 412 equivalent on wall B when dense tree crowns are present ($c_{max,exp}^+ \approx 5$ and

413 $c_{max,sim}^+ \approx 25$ for $\lambda = 200 \text{ m}^{-1}$ vs. $c_{max,exp}^+ \approx 10$ and $c_{max,sim}^+ \approx 20$ for
 414 $\lambda = 0 \text{ m}^{-1}$).

415 Figure 7 also highlights the effects of the finite length of the street canyon.
 416 The formation of the corner vortices induces a decrease of concentration
 417 distribution on walls A and B from $y/H = 0$ to the street canyon ends.
 418 According to simulation, c^+ values are on average more than 2.3 times higher
 419 in the fifth central part of wall A ($|y/H| < 1$) than on the rest of the wall
 420 when trees are present. This ratio equals 2.1 without trees. Because of
 421 the blocking effect of trees, concentration increases on wall A and decreases
 422 on wall B for $|y/H| > 2.5$. Such a trend is also highlighted in experimental
 423 results, although the measured c^+ show smoother gradients in the y direction
 424 in the central part of the canyon than simulated, especially when trees are
 425 present. Simulation results also exceed experimental data on wall B at this
 426 location.

427 On average, comparing simulation results to measurements, results show
 428 that simulation satisfactorily predicts wall averaged concentration on wall A
 429 ($\overline{c_{sim,A}^+} = 18.6$ vs $\overline{c_{exp,A}^+} = 19.6$), but overpredicts that of wall B ($\overline{c_{sim,B}^+} = 9.6$
 430 vs $\overline{c_{exp,B}^+} = 5.4$) in the absence of trees. Including trees in the modeling also
 431 induce a limited relative modification of concentration levels on walls A and
 432 B compared to the experiment: $\overline{c_{sim,A}^+}$ increases by 18 % and 23 %, and $\overline{c_{sim,B}^+}$
 433 decreases by 11 % and 15 %, for $\lambda = 80$ and 200 m^{-1} respectively according
 434 to current results, whereas $\overline{c_{exp,A}^+}$ increases by 41 % and 58 %, and $\overline{c_{exp,B}^+}$
 435 decreases by 37 % and 49 %, for $\lambda = 80$ and 200 m^{-1} respectively according
 436 to Gromke et al. (2008) and Gromke and Ruck (2009).

437 [Figure 8 about here.]

438 To compare observations and predictions in more details, Figure 8 pro-
439 vides c^+ profiles at different locations on walls A and B. As expected from
440 Figure 8, simulations and observations match quite well on wall A with the
441 exception of $y/H = 1.26$, where simulation results are about the half of the
442 measured values for the densest tree configuration. Conversely to wall A,
443 simulation results exceed measurements on wall B, especially next to the
444 floor, with a relative deviation often greater than a factor of 2. The same
445 behavior was observed in the LES results of Salim et al. (2011) for wall B
446 in the presence of tree plantings. Current simulation results even show an
447 inverse effect of trees at $y/H = 0.05$ and 0.45 compared to measurements.
448 With respect to Moonen et al. (2013), current results are in closer agreement
449 with experimental data in the central part of the street canyon, but deviate
450 more around $y/H = 1.26$.

451 *Quantitative evaluation.*

452 [Figure 9 about here.]

453 Figure 9 summarizes the quality metrics defined in Table 2 computed for
454 both or only wall A and wall B, along with values available in literature that
455 were obtained by Moonen et al. (2013) and Kang et al. (2017). Results show
456 that current quality metrics mostly belong to the recommendation ranges
457 when considering both walls A and B. However, wall-by-wall results analy-
458 sis confirms previous statements: quality metrics are mostly close to target
459 values for wall A but half of indicators fall out of recommendation ranges
460 for wall B, for which reference concentrations used for scaling are low. Also,
461 the denser the crowns, the further apart the predictions from experimental

462 data are. The same observations holds for previously existing simulations
463 (Moonen et al., 2013; Kang et al., 2017).

464 More specifically, VG and R generally belong to the recommendation
465 ranges. These results show that predictions and experimental data are well
466 correlated, which is a necessary condition to guarantee the effective perfor-
467 mance of the model. FAC2 and RNMSE also mostly belong to the recom-
468 mendation ranges. Deviation occurs mainly on wall B for the densest tree
469 configuration. The good performance of FAC2 is an important information
470 regarding the general performance of the model as this value is not very in-
471 fluenced by outliers. RNMSE confirms previous conclusions relative to the
472 acceptability of the relative scatter. FB and MG show the least satisfactory
473 agreement between numerical and experimental data, as prediction fall out
474 of recommendation ranges when trees are present and for wall B. These re-
475 sults characterize a systematic error. The negative values of FB on wall B
476 clearly reflect the overprediction of concentration at this location. Nonethe-
477 less, according to Figure 9, present simulations show an overall comparable
478 performance as most accurate literature references.

479 *Summary.* Hence, similarly to most of reference computational studies, sim-
480 ulation results satisfactorily agree with experimental data in terms of trends
481 and concentration levels without trees and on wall A, which is the most
482 critical location in terms of exposure problems as the highest concentration
483 levels occur there. Predictions and observations deviate more on wall B,
484 which shows lower concentration levels. On average, effects of trees appear
485 accurately reproduced as simulation shows increased concentration levels on
486 wall A and slightly reduced concentration levels on wall B when trees are

487 present, but trees are found more influential in the experiments.

488 Differences between predictions and observations may be explained by
489 some modeling assumptions, which do not strictly correspond to the exper-
490 imental configuration. In particular, deviation might be explained, at least
491 partly, by the fact that a smooth boundary condition was specified at walls
492 A and B in the numerical model, which appears not to be exactly the case
493 in the experiment according to Figure 1(b): joints between blocks as well as
494 taps modify the Plexiglas wall surface. Also, roughness on the street canyon
495 floor differs from around in the experiment while a uniformly rough floor was
496 assumed in the numerical model. In addition, regarding the effect of trees,
497 the metallic lattice is not taken into account in the present numerical model
498 whereas wind tunnel experiments found that the presence of the empty lat-
499 tice cage induces an increase of pollutant concentration by 18 % on wall A
500 and a decrease of 16 % on wall B with respect to the fully empty case. Thus,
501 the accumulation of these apparently small differences in the geometric mod-
502 els could lead to significant deviation in concentration results by modifying
503 flow properties in the street canyon.

504 **5. Physical analysis of flow and concentration fields**

505 Results presented in Section 4.3 pointed out effects of trees as well as
506 of the finite length of the canyon on the distribution and level of pollutant
507 concentration at walls. These modifications being due to changes in air
508 flows in the street canyon, this section analyses the flow field induced by the
509 different configurations to highlight basic turbulent dispersion mechanisms
510 as made possible by LES.

511 *5.1. Air flow structures*

512 [Figure 10 about here.]

513 According to the mean velocity streamlines shown in Figure 10, the flow
514 resistance induced by tree crowns limits the formation of the street canyon
515 vortex, blocks corner eddies and modifies the flow structure in the lower part
516 of the canyon. In the presence of trees, the street canyon vortex is deformed
517 and its center shifted towards wall B. This alteration of the vortex structure
518 around $y/H = 0$ leaves more room to a weak secondary recirculation in the
519 bottom upstream part of the canyon, and modifies the mixing layer at its
520 top.

521 [Figure 11 about here.]

522 The effect of trees on turbulent structures can be more clearly identified
523 in Figure 11, which compares instantaneous 3D isocontours of Q criterion
524 ($Q = 5 \times 10^4$) to identify coherent structures within the street canyon and in
525 the mixing layers bounding it. Results show that, after separation at the top
526 and side leading edges of block A, the turbulent structures develop differently
527 downstream in the street canyon depending on the configuration. Coloration
528 by w^+ suggests that a 3D canyon and corner vortices develop, with eddies
529 filling all the street canyon volume in the absence of trees. In the presence
530 of trees, these turbulent structures are no more visible next to wall A due to
531 the blocking effect of trees.

532 [Figure 12 about here.]

533 To evaluate more quantitatively the effects of trees on turbulence, Fig-
 534 ure 12 depicts boxplots of instantaneous velocity components normalized by
 535 U_H (u^+ , v^+ , w^+) in the center of the street canyon ($y/H = 0$) or at the street
 536 canyon ends ($y/H = 5$). Two points are more particularly emphasized in
 537 Figure 12(a): point M is located in the middle of the street canyon and point
 538 A is located in the bottom leeward part of the street canyon, i.e. where con-
 539 centrations are the highest. The central line of boxplots indicate the median
 540 value, the circle corresponds to the mean value, boxplot edges are the 25
 541 and 75 percentiles and the ends of the whiskers represent the extreme values.
 542 Crosses are related to outliers.

543 As expected, results show that mean velocity and fluctuations are gener-
 544 ally higher at $y/H = 5$ than at $y/H = 0$ for both points M and A. The
 545 direct lateral interactions with the general boundary layer, induces standard
 546 deviations that are generally more than 3 times higher at $y/H = 5$ than at
 547 $y/H = 0$. Without trees, the corner vortex also induces relatively high mean
 548 velocities at point M ($v = -1.25 \text{ m s}^{-1}$) as the flow enters the street canyon
 549 from its sides. On the contrary, velocity at point M is rather low at $y/H = 0$,
 550 because the canyon vortex is almost centered in the canyon. Being located
 551 on the edge of this vortex, point A shows higher velocities ($u = -0.35 \text{ m s}^{-1}$).

552 Regarding the effects of trees, Figure 12 confirms previous results: trees
 553 significantly alter mean velocities as well as fluctuations at point M, which
 554 is located in tree crowns. More specifically, at $y/H = 0$, the alteration of the
 555 canyon vortex due to the presence of dense trees reduces u by a factor of 7 at
 556 point M, i.e. down to nearly zero (with a change of sign), while w is increased
 557 by a factor of 17, making w non null. Corresponding standard deviations are

558 divided by a factor about 5 for both components. Regarding point A, u is
559 divided by a factor of 6 and w is reduced by a factor of 2. Standard deviations
560 are less altered by trees than for point M, as they are reduced by less than
561 15 % and 30 % respectively for u and w . Standard deviation is even increased
562 by 35 % for v . At $y/H = 5$, tree crowns limit v at point M by a factor of
563 3 and u by a factor of 12 (with a change of sign). Corresponding standard
564 deviations are reduced by a factor of 1.6. Considering point A, u and w are
565 reduced by less than a factor of 2, and v by a factor of 6 (with a change of
566 sign). Standard deviations are only reduced by 10 % for u and w and by 20 %
567 for v .

568 Hence, these results highlight that trees alter velocities at points A and
569 M, which is related to the alteration of the general flow structures in the
570 middle and at the end of the canyon, i.e. in the canyon and the corner
571 vortices. However, while both mean velocities and fluctuations at point M
572 are generally reduced because of tree crowns, effects of trees on fluctuations
573 at point A are less straightforward.

574 5.2. *Effect of turbulence on dispersion*

575 [Figure 13 about here.]

576 According to Figures 10 and 7, clean air entering the canyon from above
577 in front of the windward wall and from the sides of the street canyon pushes
578 pollutant towards the central leeward part of the canyon. A jet raises there
579 and drives the pollutant out, especially when trees are present. Focusing on
580 this critical part of the street canyon, Figure 13 clearly shows how the re-
581 duction of turbulence and velocities induced by tree crowns affect pollutant

582 dispersion. The reduced ventilation potential of the street canyon increases
583 pollutant concentration levels within it. More precisely, while pollutant is
584 driven by the main street canyon vortex from line sources to the top mixing
585 layer in the absence of trees, porous zones favor the diffusion and the resi-
586 dence of pollutant inside the street canyon. The less porous the crown, the
587 higher the concentration. Pollutant is especially retained below and inside
588 tree crowns, as well as in the leeward part of the street canyon. The flow
589 developing there extends further above wall A at the canyon top and in the
590 mixing layer, which contaminates the separation bubble above block A.

591 [Figure 14 about here.]

592 Similarly to Section 5.1, Figure 14 displays boxplots of instantaneous c^+ at
593 $y/H = 0$ or at the street canyon ends ($y/H = 5$) for a point M and A in order
594 to analyze more quantitatively the effects of trees on turbulent dispersion
595 processes. As opposed to velocity, and as highlighted in Section 4.3, results
596 show that concentration levels are about one order of magnitude higher at
597 $y/H = 0$ than at $y/H = 5$ for point M, where concentration at $y/H =$
598 5 are very low. This difference is also substantial at point A, for which
599 concentration levels at $y/H = 5$ are also low. The denser the crowns, the
600 greater the difference. Standard deviations are also significantly higher at
601 $y/H = 0$ than at $y/H = 5$.

602 Still conversely to velocity, the influence of trees on concentration differs
603 depending on the considered location: tree crowns increase concentration
604 levels at $y/H = 0$ and slightly decrease it at $y/H = 5$ for points A and M.
605 More specifically, at $y/H = 0$, dense tree crowns increase mean concentration

606 by a factor of 2 at point M and 1.8 at point A compared with the configu-
607 ration without trees. Corresponding standard deviations are increased by a
608 factor of 2.7 and 1.3 respectively. Reached peak values are very high as c^+
609 substantially exceeds 100 several times when trees are present, even if mean
610 concentrations may be less than the half of this peak value.

611 Hence, the reduction of velocities by trees tends to increase mean con-
612 centration *and* associated fluctuations at $y/H = 0$, i.e. where concentration
613 levels are the highest. Very high instantaneous concentrations might oc-
614 cur at point A, where the mean concentration levels significantly exceed the
615 median values. This means that instantaneous concentration can be much
616 higher than the mean value, which can be prejudicial for people's health in
617 case of short time exposure to some specific pollutants.

618 **6. Concluding remarks**

619 This study assesses the performance of a LBM-LES approach in pre-
620 dicting pollutant dispersion in street canyons in the presence or absence of
621 trees. Simulation results compare very satisfactorily to state-of-the-art re-
622 sults obtained for the same benchmark configurations using Navier-Stokes-
623 based LES approaches. Predictions exhibit a very satisfactory agreement
624 with experimental data on wall A, which is critical as this wall shows the
625 highest concentration levels, while larger differences are observed on wall B
626 (as in all previously reported numerical results), where concentration lev-
627 els are relatively low. The general effect of crowns on dispersion observed
628 in the experiment is well reproduced by simulations, but with less accuracy
629 when decreasing crown permeability. This deviation may be explained, at

630 least partly, by differences between the numerical and experimental models,
631 as the flow, and thus dispersion processes, are very sensitive to geometric
632 details at this scale.

633 Further, present results show that the developed unsteady high-fidelity
634 approach is valuable to predict and understand air flows and dispersion pro-
635 cesses and thus the local urban breathability (Panagiotou et al., 2013). In
636 particular, effects of tree crowns on the development of usual canyon and
637 corner vortices have been studied in detail. The analysis of the results es-
638 pecially pointed out the alteration of the general mean flow structures as
639 well as of intermittent processes at different locations in the street canyon.
640 Such results enable turbulent dispersion to be better predicted, and rapid
641 phenomena that are critical for short term exposure issues to be identified.

642 Hence, this study shows that the LBM-LES yields state-of-the-art results,
643 while allowing the use of very fine spatial and temporal resolutions thanks
644 to its computational efficiency. In addition, the use of embedded uniform
645 meshes with immersed boundary conditions allows to handle complex ge-
646 ometries in a very easy way, which reduces pre-processing efforts for urban
647 problems. Therefore, based on present results, this approach appears well
648 suited to further study dispersion in realistic urban environments including
649 complex building and street geometries, different atmospheric stability states
650 or even moving bodies such as motorized engines or people.

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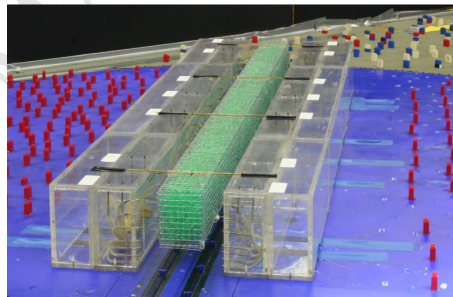
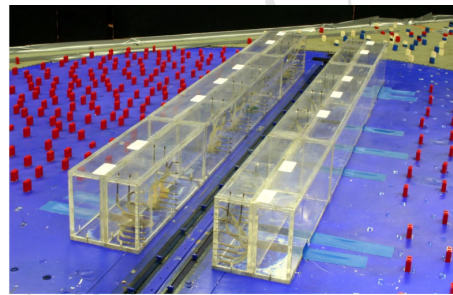
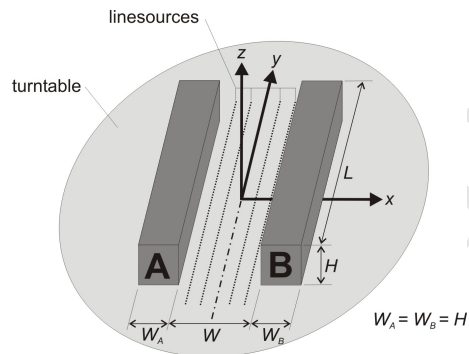
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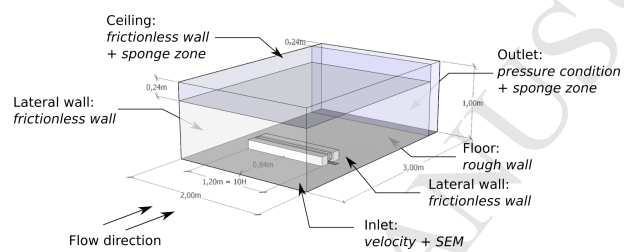
843 **List of Figures**

844	1	CODASC experimental model ©CODASC, KIT.	42
845	2	Numerical model: general dimensions and boundary conditions	43
846	3	Specific dimensions of the virtual street canyon	44
847	4	Computational mesh (5 refinement levels, $dx = H/96$)	45
848	5	Comparisons between measured (■) and simulated c^+ vertical	
849		profiles for the coarse (—) and fine (—) grid	46
850	6	Comparison between measured (left - (Gromke et al., 2008))	
851		and simulated (right) w^+ contours in the plane $y/H = 0.5$. . .	47
852	7	c^+ contours for $\lambda = 0 \text{ m}^{-1}$, $\lambda = 80 \text{ m}^{-1}$ and $\lambda = 200 \text{ m}^{-1}$,	
853		experimental Figure ©(KIT, 2017)	48
854	8	Comparison between measured and simulated c^+ vertical profiles	49
855	9	Comparison of quality metrics obtained using ProLB with re-	
856		sults of Moonen et al. (2013) and Kang et al. (2017)	50
857	10	Simulated mean velocity streamlines: 3D view (left) and in a	
858		2D plane (right)	51
859	11	3D isocontours of the Q criterion ($Q = 5 \times 10^4$) colored by	
860		w^+ , the facing section correspond to $y/H = -5$	52
861	12	Boxplot of instantaneous velocity components at points A and	
862		M	53
863	13	Simulated instantaneous (left) and mean (right) c^+ fields in	
864		the $y/H = 0$ plane	54
865	14	Boxplot of instantaneous concentration (c^+)	55

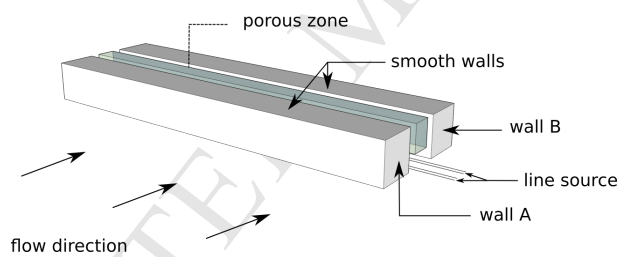


(a) Identification of blocks A and B and coordinate system (b) Pictures of the experimental setup

Figure 1: CODASC experimental model ©CODASC, KIT.



(a) General model settings



(b) Street canyon model

Figure 2: Numerical model: general dimensions and boundary conditions

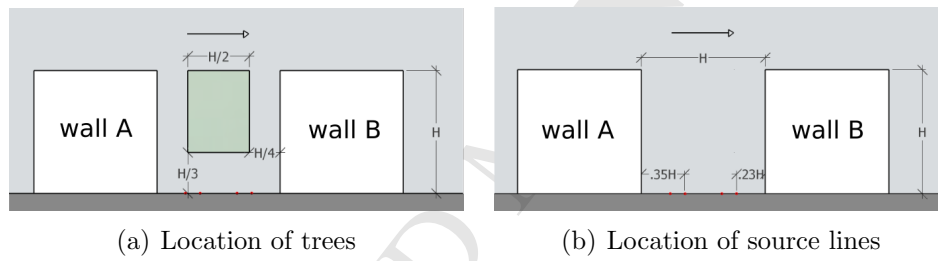


Figure 3: Specific dimensions of the virtual street canyon

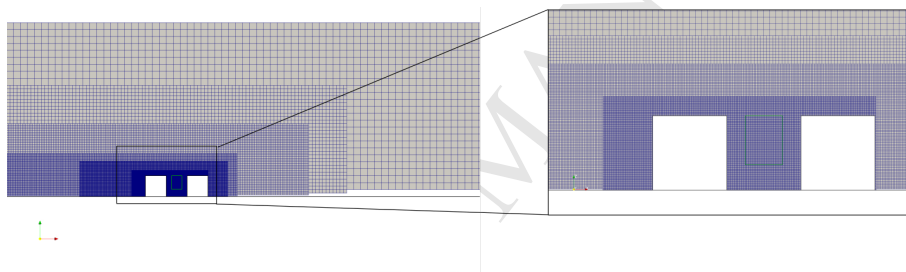


Figure 4: Computational mesh (5 refinement levels, $dx = H/96$)

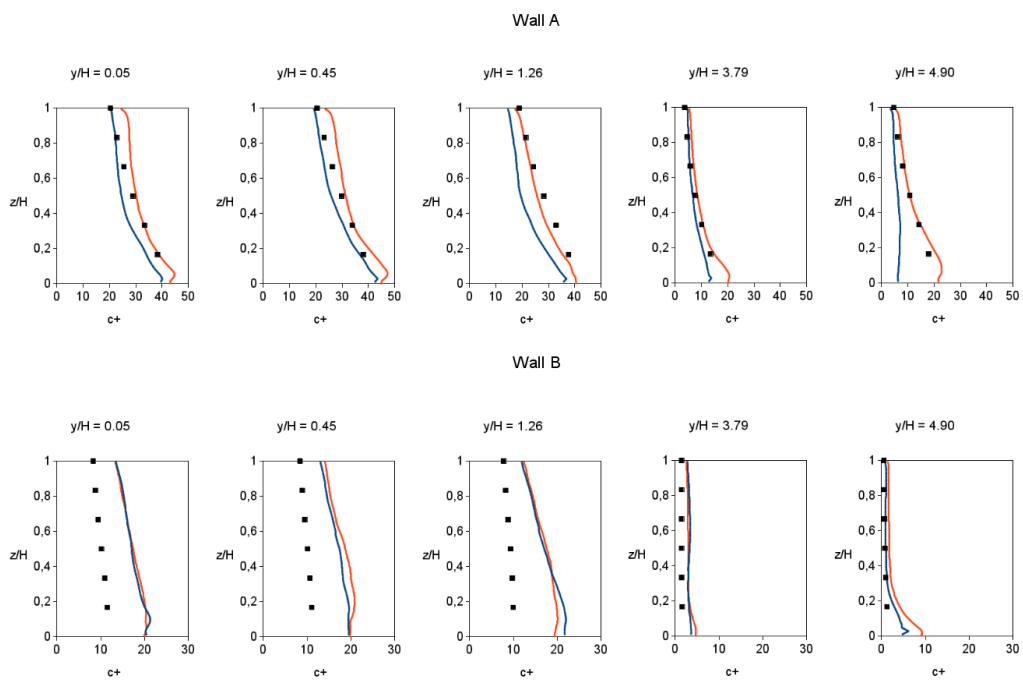


Figure 5: Comparisons between measured (■) and simulated c^+ vertical profiles for the coarse (—) and fine (—) grid

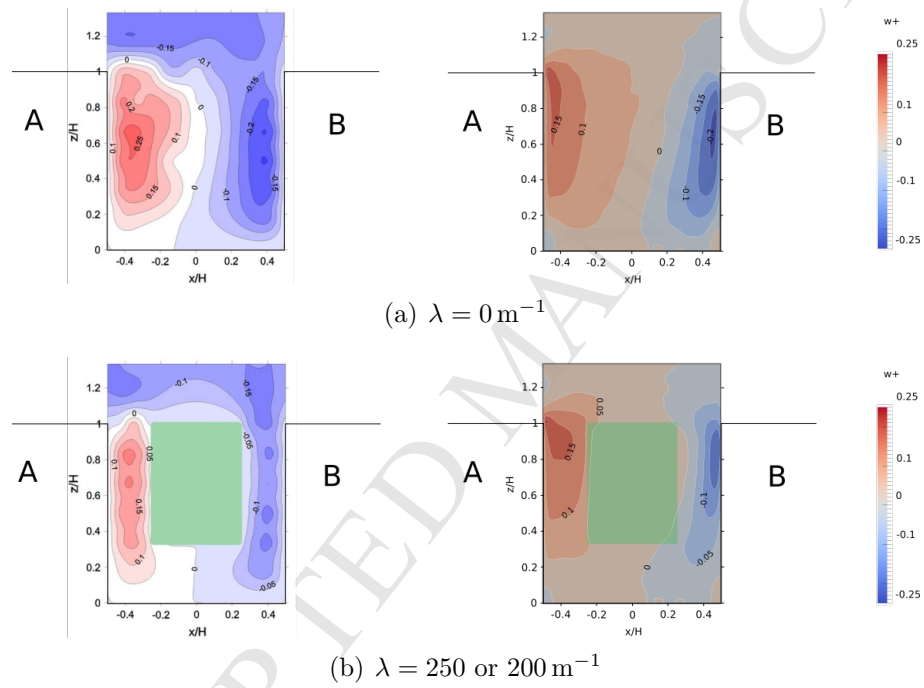


Figure 6: Comparison between measured (left - (Gromke et al., 2008)) and simulated (right) w^+ contours in the plane $y/H = 0.5$

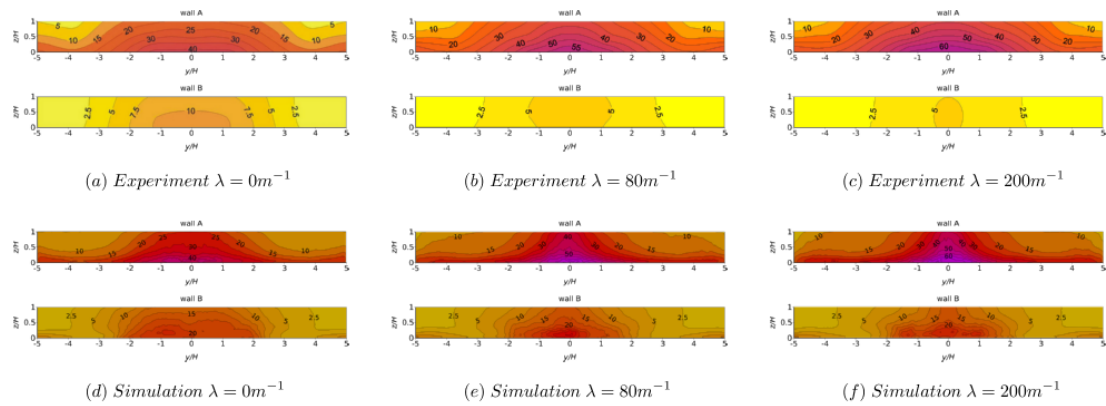


Figure 7: c^+ contours for $\lambda = 0 \text{ m}^{-1}$, $\lambda = 80 \text{ m}^{-1}$ and $\lambda = 200 \text{ m}^{-1}$, experimental Figure ©(KIT, 2017)

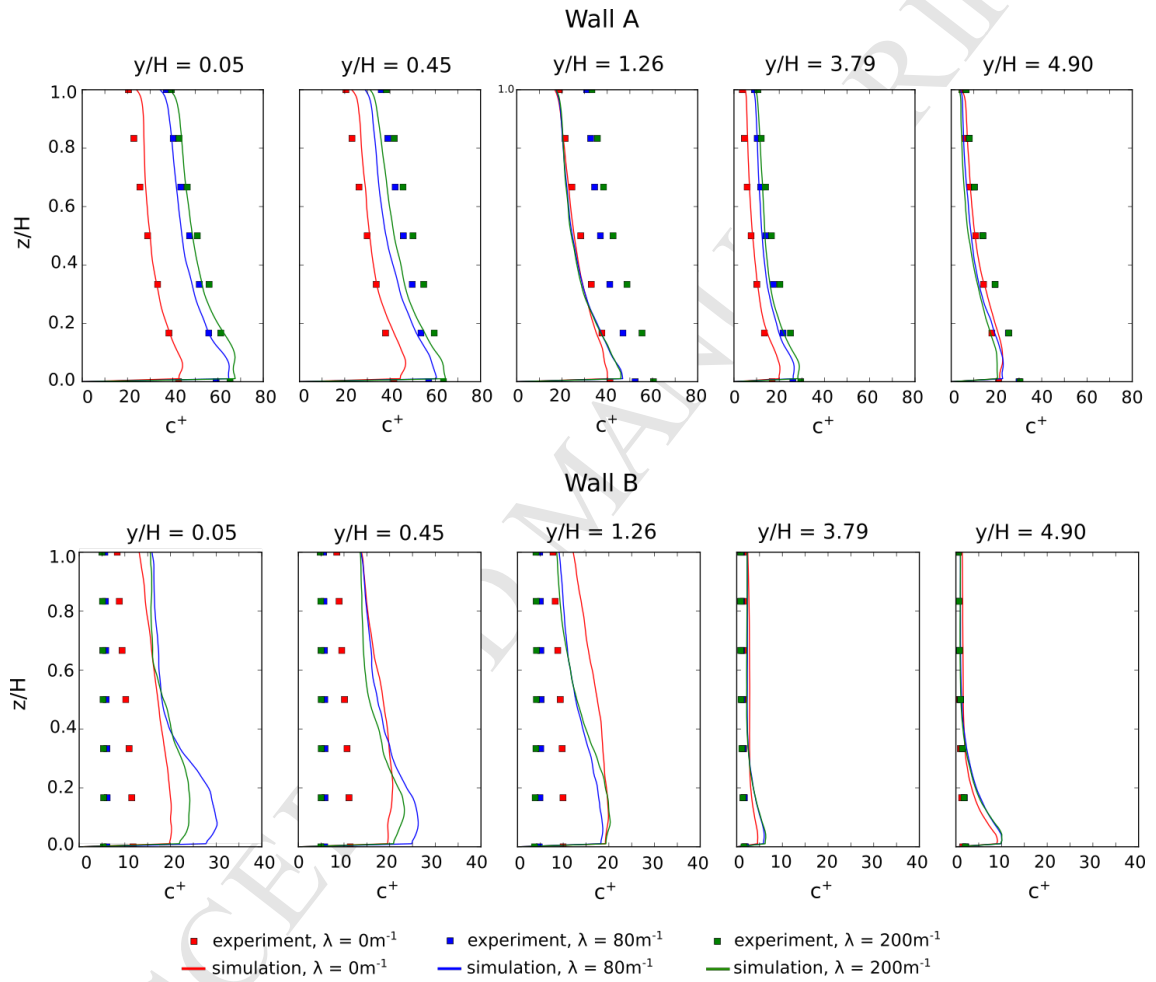


Figure 8: Comparison between measured and simulated c^+ vertical profiles

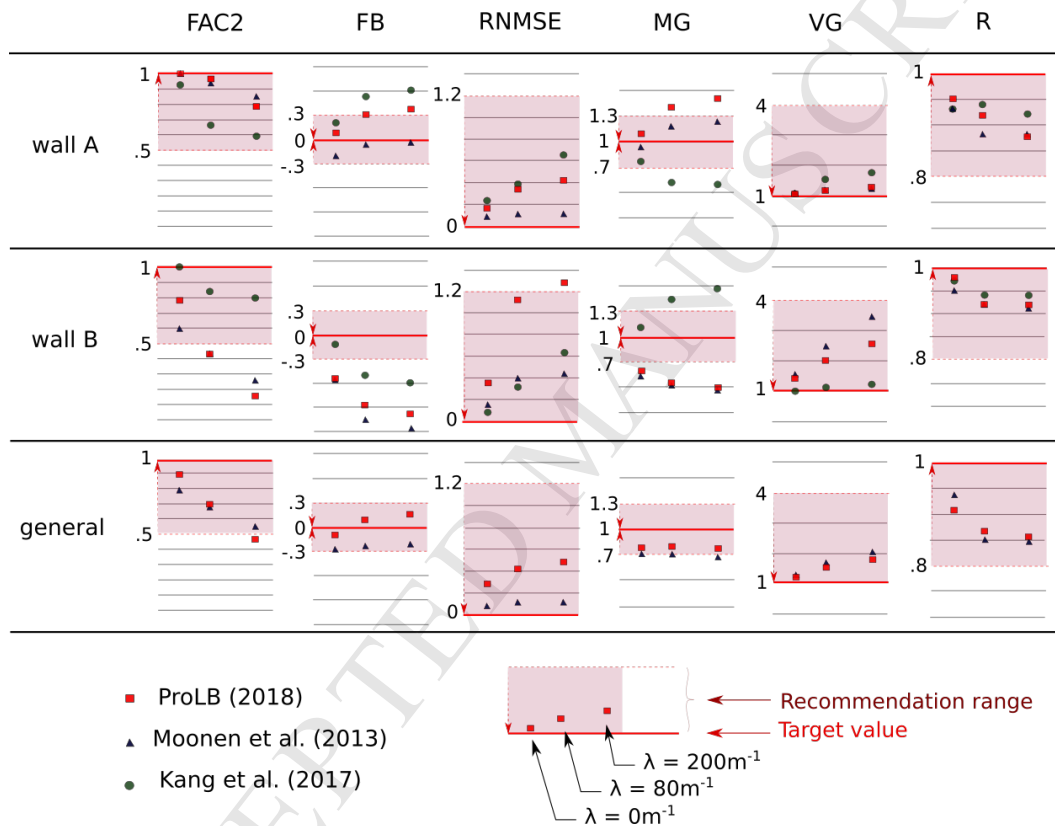


Figure 9: Comparison of quality metrics obtained using ProLB with results of Moonen et al. (2013) and Kang et al. (2017)

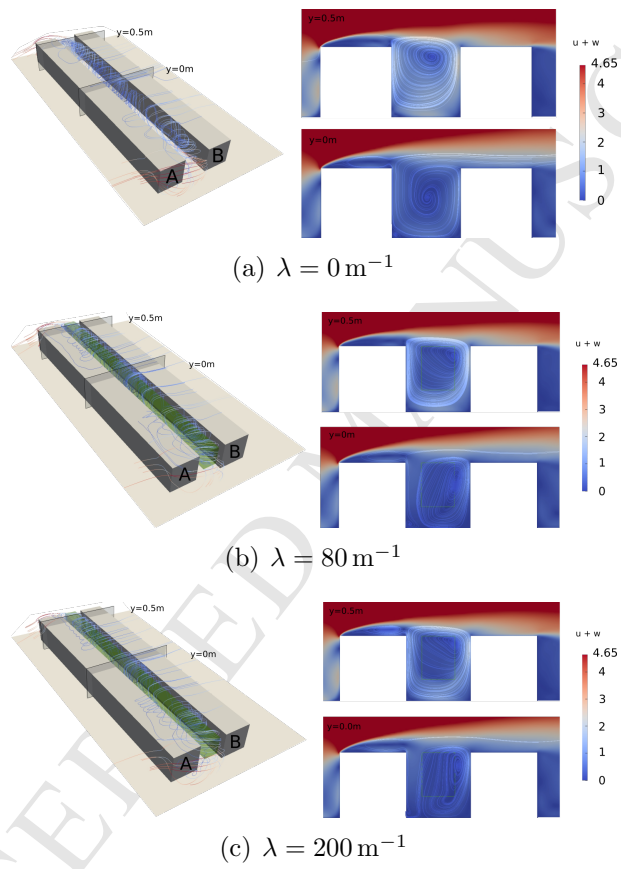


Figure 10: Simulated mean velocity streamlines: 3D view (left) and in a 2D plane (right)

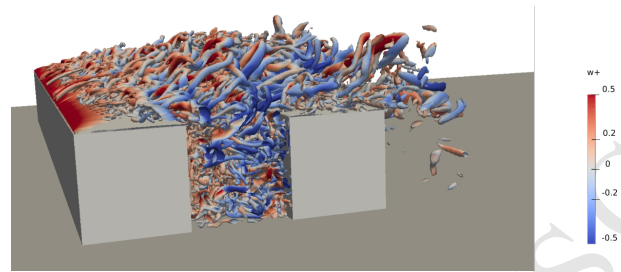
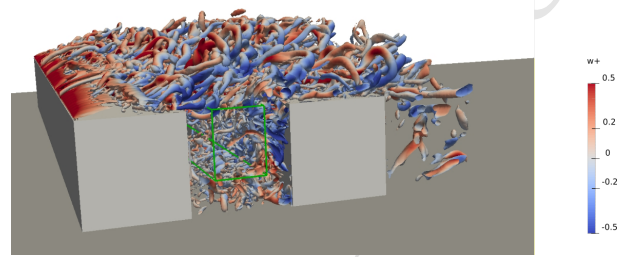
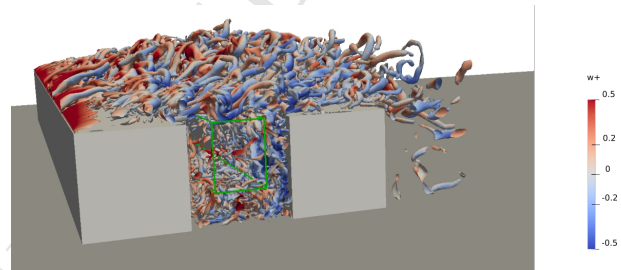
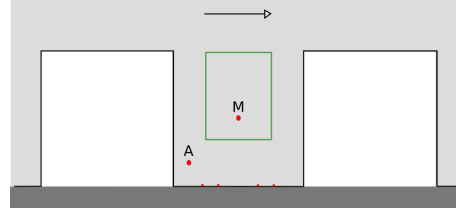
(a) $\lambda = 0 \text{ m}^{-1}$ (b) $\lambda = 80 \text{ m}^{-1}$ (c) $\lambda = 200 \text{ m}^{-1}$

Figure 11: 3D isocontours of the Q criterion ($Q = 5 \times 10^4$) colored by w^+ , the facing section correspond to $y/H = -5$



(a) Location of points A and M

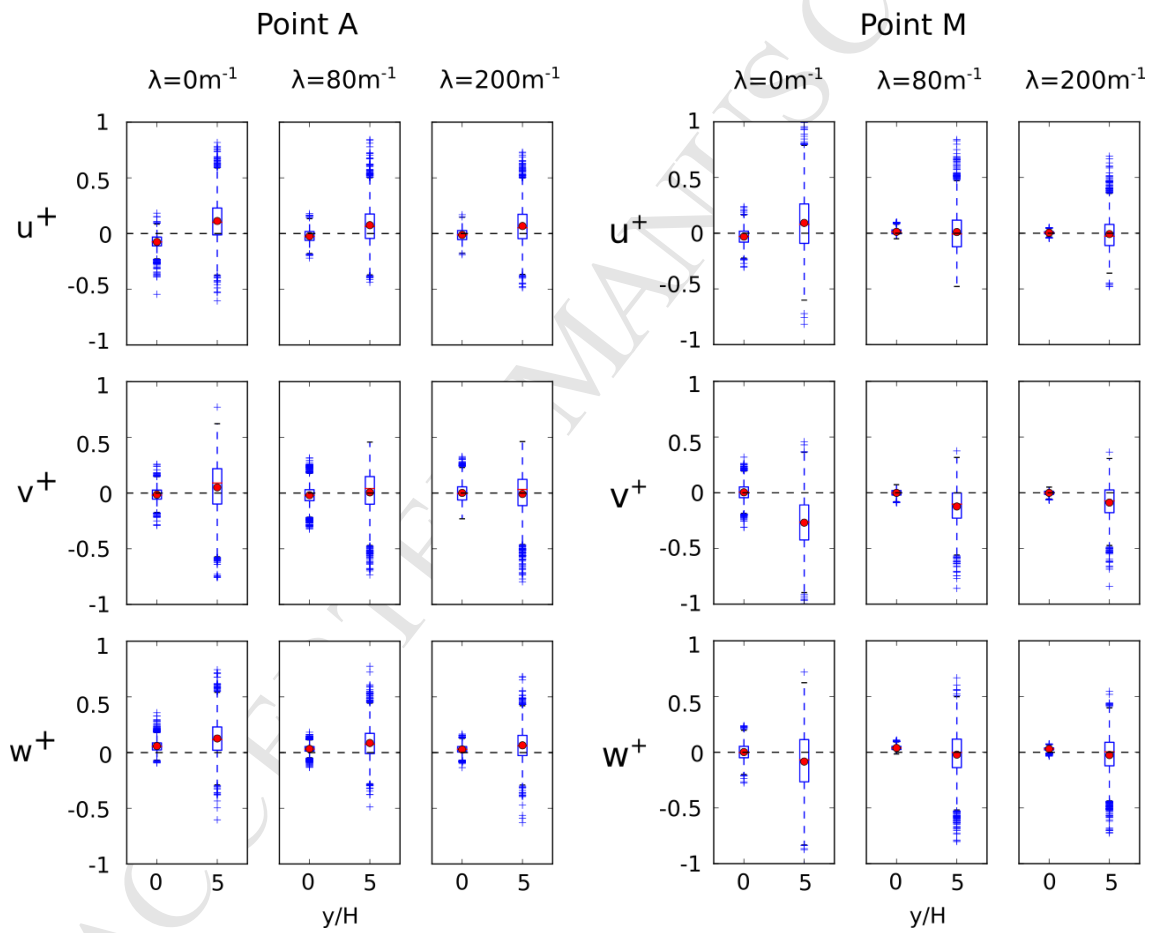
(b) Boxplot of u^+ , v^+ , w^+

Figure 12: Boxplot of instantaneous velocity components at points A and M

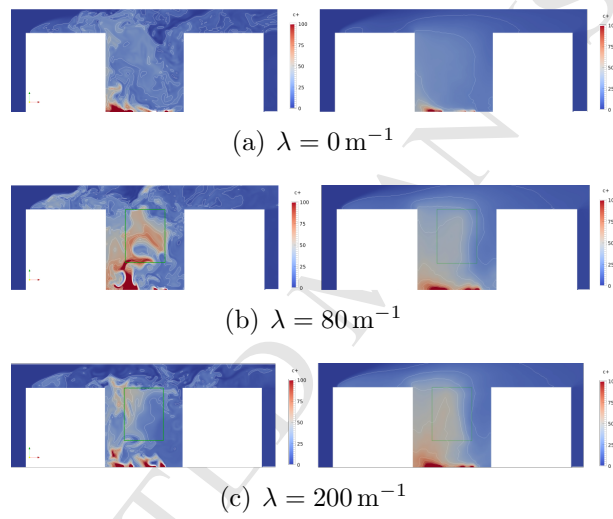


Figure 13: Simulated instantaneous (left) and mean (right) c^+ fields in the $y/H = 0$ plane

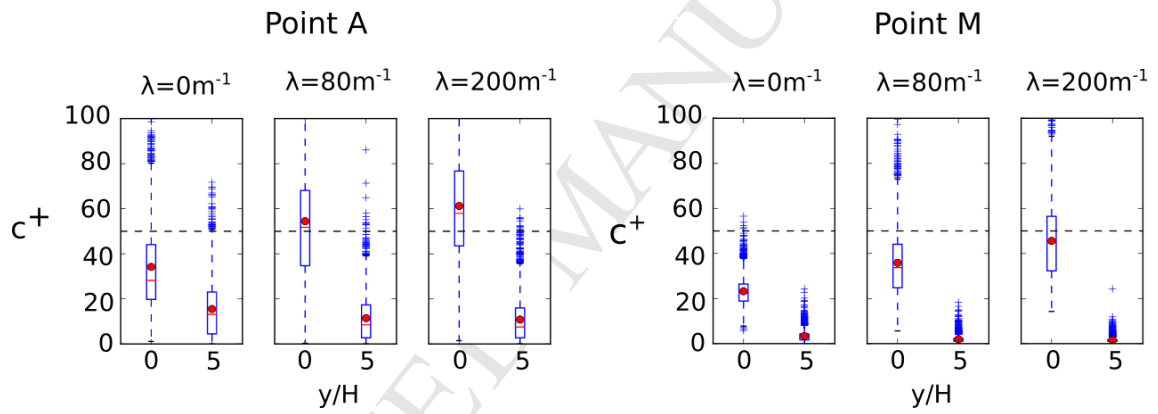


Figure 14: Boxplot of instantaneous concentration (c^+)

866 **List of Tables**

867	1	Overview of CFD studies dealing with the CODASC bench-	
868		mark, $H/W=1$, trees and a wind perpendicular to the street	
869		canyon	57
870	2	Statistical model performance indicators	58
871	3	Statistical model performance indicators computed for the coarse	
872		and fine grid at both wall in the tree free configuration	59

Reference study	Code	CFD technique	Turbulence Model	scale H [m]	Trees λ
(Gromke et al., 2008)	Fluent	RANS	$k - \epsilon$, RSM	1:1	0, 250, ∞
(Balczó et al., 2009)	MISKAM	RANS	$k - \epsilon$	1:1	0, 80, 200, 250
(Salim et al., 2011)	Fluent	RANS LES	$k - \epsilon$, RSM dyn Smago	1:150	0, 80, 200
(Moonen et al., 2013)	Fluent	LES	dyn. Smago	1:150	0, 80, 200, ∞
(Gromke and Blocken, 2015a)	Fluent	RANS	realizable $k - \epsilon$	1:150	80
(Vranckx et al., 2015)	SimpleFOAM	RANS	$k - \epsilon$	1:1	
(Kang et al., 2017)	-	URANS	RNG $k - \epsilon$	1:1	0, 80, 200

Reference study	Mesh type	dx min [m]	dt min [s]	number of cells	sim. time [s]	source model
(Gromke et al., 2008)	hexa	H/20 (x, z) H/2 (y)	-	3×10^5	-	
(Balczó et al., 2009)	hexa	H/180 (x, z) H/90 (y)	-	5.8×10^6	-	source cell no momentum
(Salim et al., 2011)	cubic	H/13	- 1/8	1.2×10^6	- 20+20	source cell
(Moonen et al., 2013)	cubic	H/24	1.25×10^{-3}	1.2×10^6	10+10	point source, flow rate + concentration
(Gromke and Blocken, 2015a)	cubic	H/20	-		-	ground line mass flux SF6
(Vranckx et al., 2015)	hexa + unstructured	H/35 (z) H/20 (x, y)	-	5×10^6	-	mass flux
(Kang et al., 2017)	hexa	H/12 (x, z) H/4 (y)		6×10^6	7.2×10^3	source cell

Table 1: Overview of CFD studies dealing with the CODASC benchmark, H/W=1, trees and a wind perpendicular to the street canyon

Metric	Aim	Range	Formula	Meaning
FAC2	1	> 0.5	$FAC2 \Rightarrow 0.5 \leq \frac{C_p}{C_o} \leq 2$	general accuracy
FB	0] - 0.3, 0.3[$FB = \frac{C_o - C_p}{0.5(\overline{C_o} + \overline{C_p})}$	mean relative bias
RNMSE	0	< 1.2	$RNMSE = \sqrt{\frac{(C_o - C_p)^2}{C_o C_p}}$	relative scatter
MG	1]0.7, 1.3[$MG = \exp(\ln C_o - \ln C_p)$	mean relative bias
VG	1	< 4	$VG = \exp[(\ln C_o - \ln C_p)^2]$	relative scatter
R	1	> 0.8	$R = \frac{(C_o - \overline{C_o})(C_p - \overline{C_p})}{\sigma_{C_p} \sigma_{C_o}}$	linear correlation

Table 2: Statistical model performance indicators

Metric	Aim	Coarse Grid	Fine Grid
FAC2	1	0.845	0.896
FB	0	0.056	-0.1
RNMSE	0	0.421	0.279
MG	1	0.923	0.784
VG	1	1.306	1.231
R	1	0.804	0.908

Table 3: Statistical model performance indicators computed for the coarse and fine grid at both wall in the tree free configuration

Highlights:

- Pollutant dispersion in a street canyon using LES lattice Boltzmann method
- Rigorous model performance assessment with respect to wind tunnel measurements
- Analysis of the impact of trees on the fluctuating and time averaged velocity fields
- Analysis of the impact of trees on dynamic pollutant dispersion processes
- LBM-LES appears well suited for pollutant dispersion studies with tree plantings

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