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# Large-eddy simulation of the urban boundary layer using drag-porosity modelling

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## Abstract

This work details the assessment of the performance of the drag-porosity model implemented in ARPS (Advanced Regional Prediction System) atmospheric Large-Eddy Simulation (LES) solver for simulating the atmospheric boundary layer developing over the urban canopy with comparison with literature. The flow within and above an idealized urban canopy consisting of a staggered array of cubes with various packing densities modelled with the drag-porosity approach immersed into a neutral, Coriolis-free atmospheric boundary layer at high Reynolds is investigated. Besides one-points statistics, particular interest was given to the ability of the model to reproduce the turbulent coherent structures and their characteristic scales. A detailed analysis of one-point statistics, one- and two-dimensional spectra and two-point correlation functions revealed the presence of typical structures and features found in wall-bounded turbulent flows (two-scale behavior in the roughness sublayer, ejections, sweeps, self-similar wall-attached large scale streaky motions, canopy-independent very large scale motions). Further investigation to identify the interaction mechanisms between large and small scales based on spectral filtering highlighted an interaction mechanism that resembles an amplitude modulation process, as observed in literature on wall-bounded flows. These findings therefore show that the proposed approach is able to reproduce all the key features of the flow developing over urban terrain.

**Keywords:** Atmospheric boundary layer, Drag-porosity, Large-eddy simulations, Turbulent flows

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## 1. Introduction

The numerical modelling of turbulent transport and mixing processes resulting from the interaction between urban areas and the atmospheric boundary layer (ABL) is of great importance for air quality assessment, micro-climate predictions and more generally for environmental wind engineering and structural design (Blocken 2014; Thordal et al. 2019; Potsis et al. 2023). A wide range of scales, from the large coherent structures of the atmospheric boundary layer to the smaller ones generated within the urban canopy, are involved in the unsteady transfers of mass, heat and momentum. Despite the rapid growth in computing power over the past decades, the simulation of all scales and their dynamical interactions remains an issue when the studied area extends to the entire city. Unsteady approaches such as large-eddy simulations (LES) that solve the flow characteristics around urban elements are generally limited to the size of a single neighbourhood (Nozu and Tamura 2012; Giometto et al. 2016; Tolia et al. 2018). Considering

18 the scale of the city makes it difficult to detail all the roughness elements. The main issue of the urban boundary layer  
19 simulations is thus to model the unsteady scale interactions in such a way that the high heterogeneity of urban areas  
20 and their morphological characteristics can be accounted for without necessarily simulating all the details of the flow  
21 within the canopy layer. The main objective of the present contribution is therefore to assess and demonstrate the  
22 performance of using a drag-porosity approach to model the urban-canopy influence onto the lower atmosphere. The  
23 focus is on the capacity of this approach in a LES atmospheric boundary-layer model to represent the main turbulent  
24 flow features within the roughness sublayer (RSL) with varying building packing density.

25 The development of urban canopy models in mesoscale models was first motivated by the need to properly account  
26 for the influence of neighbourhood heterogeneity on turbulent mixing and transport, by avoiding the classical constant-  
27 flux layer assumption enforced by the Monin-Obukhov similarity theory and thus representing the mean wind and  
28 turbulence over the entire thickness of the urban canopy layer (UCL) (Martilli et al. 2002; Otte et al. 2004; Coceal and  
29 Belcher 2004; Santiago and Martilli 2010). The dynamic component of these urban canopy models was inspired by the  
30 drag approach initially developed for plant canopies, in which the influence of the vegetation on the flow was modelled  
31 through a drag force introduced in the Reynolds averaged momentum equations and proportional to a constant drag  
32 coefficient, the plant area density and the square of the mean wind speed (see e.g. Wilson and Shaw 1977). Originally  
33 based on the intuition of adding a new term into the Reynolds averaged equations to account for the drag force, the  
34 drag model was then justified by later works of Raupach and Shaw (1982), Hiraoka (1993) and Finnigan and Shaw  
35 (2008). In particular, the double-averaging method that they proposed yields naturally the appearance of an additional  
36 term in the double-averaged momentum equations that can be identified as a drag force term.

37 As for the unsteady modelling of turbulent flows, the drag force approach applied to plant canopies has been used  
38 for many years in LES atmospheric models and has proved its effectiveness to represent the turbulent transfers within  
39 and above the roughness sublayer (see e.g. Shaw and Schumann 1992; Yue et al. 2007; Dupont and Brunet 2008a,b;  
40 Liu et al. 2016). Similar approaches have been used in the context of the turbulent flow modelling over rough walls,  
41 demonstrating the suitability of a quadratic drag forcing to represent the rough-wall influence on the flow (Busse and  
42 Sandham 2012; Varghese and Durbin 2020). Finally, Bannister et al. (2021) recently used a drag approach, assuming  
43 a constant drag coefficient as in most urban canopy models (see e.g. Coceal and Belcher 2004; Otte et al. 2004), in  
44 order to study the pollution transport within urban patches of varying packing density.

45 However, the extension of the drag model from vegetated to urban canopies is not that straightforward. Unlike  
46 forest canopies which are generally considered as a porous medium represented by a vertically distributed foliar  
47 density, the urban canopy is composed of large roughness elements whose shape, spacing and arrangement influence  
48 the characteristics of the flow in the RSL and overlying boundary layer (see e.g. Cheng et al. 2007; Placidi and  
49 Ganapathisubramani 2015; Perret et al. 2019). These geometrical parameters are usually represented by the frontal  
50 density  $\lambda_f$  (defined as the ratio of the sum of windward area of the roughness elements to the total surface area) and  
51 the packing density  $\lambda_p$  (defined as the plan area occupied by the buildings relative to the total surface area). Through  
52 the compilation of results from laboratory and field experiments, Grimmond and Oke (1999) highlighted the primary

53 importance of those parameters on the aerodynamic properties of the urban areas and the link with the three flow  
54 regimes identified in Oke (1988): an isolated roughness flow regime for sparse canopies, a wake-interference regime  
55 for intermediate densities and a skimming flow regime for dense canopies. Each of these regimes influences not only  
56 the bulk flow parameters, but also the development of turbulent structures within the canopy and the interactions with  
57 the overlying layer.

58 Studies of flows over rough walls conducted via cube resolving numerical simulations (Coceal et al. 2007; Kanda  
59 2006), wind tunnel experiments (Castro et al. 2006; Blackman and Perret 2016; Basley et al. 2019) and field ex-  
60 periments (Inagaki and Kanda 2010) have shown that above the RSL, these flows present the same organization as  
61 the flows over smooth wall. It has been indeed shown that they are populated by the same type of coherent struc-  
62 tures, namely near-wall streaks and large self-similar attached eddies as in Perry and Marušić (1995), large-scale  
63 motions (LSMs) and meandering very-large scale motions (VLSMs) composed by low-momentum alternating with  
64 high-momentum narrow regions elongated in the streamwise direction as in Marusic et al. (2010), and non-linear inter-  
65 actions between large-scale momentum regions and near-wall structures through an amplitude modulation mechanism  
66 as in Mathis et al. (2011). However, important differences were observed due to obstacle-induced turbulence, which  
67 depends on the canopy-flow regime. In particular, Coceal et al. (2007) demonstrated the existence of ejection and  
68 sweep events responsible for most of the intermittent exchange of momentum between the urban-like canopy flow and  
69 the overlying layer as they are major contributors to the Reynolds shear stress. The strong shear layers that form along  
70 the top of the obstacles were evidenced by Castro et al. (2006) who observed a coexistence of two energetic scales  
71 in the RSL, the obstacle-induced small scales superimposing with the larger scales dominating the overlying layer,  
72 and referred to as a “two-scale” behavior. Using laboratory measurements of flow over various rough walls, Placidi  
73 and Ganapathisubramani (2015) performed a proper orthogonal decomposition (POD) that evidenced the existence of  
74 self-similar behavior of the most energetic modes, therefore confirming the independence of the largest scales from  
75 the roughness elements, but a morphology-dependent behavior when considering only the RSL.

76  
77 Therefore, to accurately represent the unsteady flow over an urban canopy, the parameterization of the drag force  
78 model must be adapted to account for the influence of the morphological characteristics. The urban-like canopies  
79 consisting in staggered arrays of cubes are considered here since this configuration has been thoroughly studied both  
80 experimentally and numerically by means of obstacle-resolving RANS (Santiago et al. 2008), LES (Kono et al. 2010)  
81 or direct numerical simulation (DNS) (Leonardi and Castro 2010). All of these studies reported significant variations  
82 with height of the local drag force (and hence sectional drag coefficient) and its dependency on packing density  $\lambda_p$   
83 (similar to  $\lambda_f$  in this case) that can be explained by the associated flow regimes. As discussed later by Castro (2017),  
84 the mean velocity profile within the urban canopy is not universal : it clearly differs from exponential profiles gener-  
85 ally assumed in urban canopy layer models and this is to be related to the drag coefficient profiles. Maché et al. (2010)  
86 proposed for the first time a drag model suitable for the large-eddy simulation of the urban boundary-layer (see also  
87 Maché 2012). The improvement over vegetation canopy models and current urban canopy models comes from the

88 use of a vertically distributed drag coefficient that also depends on building density. The sectional drag coefficient was  
89 deduced from the tendencies reported in the literature for various densities representative of the three flow regimes to  
90 ensure that the mean velocity profiles within the canopy layer were in agreement with those from obstacle-resolving  
91 simulations or experiments. This drag approach implemented in the LES atmospheric model ARPS (Advanced Re-  
92 gional Prediction System) is used and investigated in the present study.

93  
94 In order to demonstrate the ability of our drag-porosity approach to simulate, without any forcing other than  
95 that imposed through the drag coefficient and canopy density, the turbulent exchanges between the urban canopy  
96 and the overlying layer and the scales characteristic of the RSL, three canopy configurations are considered with  
97 packing densities of 6.25%, 25% and 44% in order to cover the three flow regimes reported by Oke (1988). The  
98 study focuses on the characteristics of the flow in the RSL above the canopy and in the overlying boundary layer. No  
99 direct comparison or analysis of the flow within the canopy will be shown as, by essence, individual buildings and the  
100 associated flow feature are not represented by the drag-porosity approach.

101 The objectives of this paper are : (i) to assess the capacity of the drag-porosity model to simulate urban turbulent  
102 flows in the roughness sublayer and the log-layer based on comparisons with literature; in particular, the existence of  
103 typical turbulent structures found in smooth- and rough-wall flows will be assessed, and (ii) to evaluate whether or not  
104 the model reproduces the impact of geometrical features on turbulence in the RSL and log-layer.

105  
106 Section 2 is dedicated to the description of the atmospheric numerical solver ARPS and the drag model used in  
107 this study. The results are given in Sect. 3, presenting a first characterisation of the boundary layer, a qualitative  
108 visualisation of flow structures via instantaneous snapshots, an investigation of the spectral content, complemented  
109 with a two-point correlations analysis, and an analysis of the inter-scale interaction mechanisms existing in the RSL  
110 through spectral filtering. Finally, conclusions are given in Sect. 4.

## 111 **2. Methods**

### 112 *2.1. Model description*

113 The code ARPS (Xue et al. 2000, 2001) used in this study is a 3D atmospheric LES model developed by the Center  
114 for Analysis and Prediction of Storms (CAPS, University of Oklahoma) which can be used for mesoscale simulations  
115 at high resolution.

116 The non-hydrostatic compressible filtered Navier-Stokes equations are solved in terrain-following coordinates.  
117 The subgrid scale (SGS) momentum fluxes are modelled by solving the SGS turbulent kinetic energy ( $e$ ) equation.  
118 Fourth-order horizontal and second-order vertical momentum and scalar advection schemes are used. Time integra-  
119 tion is performed using a leapfrog method of second order for the non-acoustic wave modes (with times steps  $\Delta t$ ),

120 while acoustic waves are integrated with smaller time steps, using a mode-splitting technique.

121  
122 The present simulations are performed under neutral atmospheric conditions so that moisture, water, snow and ice  
123 physics as well as heat transfers are disregarded and the associated conservation equations are not presented here. For  
124 the sake of clarity, the equations are presented in Cartesian coordinates.

125 Based on the drag force approach introduced in ARPS by Dupont and Brunet (2008b) the momentum equation for the  
126  $i^{th}$  component can be written as:

$$\bar{\rho} \left( \frac{\partial \tilde{u}_i}{\partial t} + u_j \frac{\partial \tilde{u}_i}{\partial x_j} \right) = F_{C_i} + F_{P_i} - \frac{\partial \tau_{ij}}{\partial x_j} - F_{D_i} \quad (1)$$

127 where tilde variables are LES-resolved variables and over-barred variables indicate the atmospheric base state that is  
128 horizontally homogeneous and constant in time, and satisfies the hydrostatic hypothesis.

129  
130 The Coriolis force term is denoted by  $F_{C_i}$  and the pressure-gradient force term  $F_{P_i}$  in equation (1) contains an  
131 artificial ‘‘divergence damping’’ term used to attenuate acoustic waves:

$$F_{P_i} = -\frac{\partial}{\partial x_i} \left( \tilde{p}'' - \alpha \frac{\partial \tilde{\rho} \tilde{u}_j}{\partial x_j} \right) \quad (2)$$

132 where double primed variables indicate the deviations from base state values. The damping coefficient  $\alpha$  depends on  
133 the minimum grid size and the acoustic (small) time step. The pressure is computed by solving equation (3) at each  
134 small time step:

$$\frac{\partial \tilde{p}''}{\partial t} + \tilde{u}_i \frac{\partial \tilde{p}''}{\partial x_i} = -\bar{\rho} c_s^2 \frac{\partial \tilde{u}_i}{\partial x_i} + \bar{\rho} g \tilde{u}_i \delta_{i3} \quad (3)$$

135 where  $c_s$  denotes the sound wave speed. Equation (3) is obtained from the equation of state and continuity equation,  
136 neglecting here the contribution of diabatic heating on pressure changes.

137  
138 The drag force component  $F_{D_i}$  introduced in equation (1) as a sink term for momentum is expressed for urban  
139 canopies as:

$$F_{D_i} = 0.5 \bar{\rho} C_d a_f \tilde{u}_i \sqrt{\tilde{u}_j \tilde{u}_j} \quad (4)$$

140 where  $C_d$  is the drag coefficient and  $a_f$  is the frontal density per unit volume defined as the ratio of the total windward  
141 area of the obstacles to the volume of fluid in a cell:

$$a_f(z) = \frac{\sum_n l_n \Delta z}{\Delta x \Delta y \Delta z - \sum_n l_n w_n \Delta z} \quad (5)$$

142 where the summation ranges over all buildings within the considered cell,  $\Delta x$ ,  $\Delta y$  and  $\Delta z$  are the longitudinal, transversal  
143 and vertical grid sizes, respectively, and  $l_n$  and  $w_n$  are the individual obstacle’s length (normal to the wind direction)  
144 and width (in the wind direction). The vertical drag force component is supposed to be small and the drag coefficient

145 in the vertical direction is set to the constant value of 1. For the horizontal components of the drag force, sectional  
 146 drag coefficients  $C_d(z)$  that depend on packing density are used and will be presented in Sect. 2.2.

147

148 The SGS stress  $\tau_{ij}$  in equation (1) is modelled by:

$$\tau_{ij} = -\bar{\rho}v_t \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \quad (6)$$

149 where the eddy viscosity  $v_t$  is modelled with a velocity scale based on the SGS turbulent kinetic energy  $e$  :

$$v_t = 0.1l_m \sqrt{e} \quad (7)$$

150 The SGS mixing length  $l_m$  depends on the grid size. Horizontal ( $l_h$ ) and vertical ( $l_v$ ) mixing lengths are distinguished  
 151 in ARPS to deal with mesh aspect ratios currently used in atmospheric applications ( $\Delta z < \sqrt{\Delta x \Delta y}$ ):  $l_h$  is considered as  
 152  $\sqrt{\Delta x \Delta y}$  while  $l_v$  is set as  $\Delta z$ . In the present application, the horizontal mesh is of the order of a few meters maximum  
 153 while the vertical stretching induces vertical grid size ranging from one meter within the canopy to hundred meters  
 154 near the top of the boundary layer. To avoid discrepancies when the mesh is such that  $\Delta z > \sqrt{\Delta x \Delta y}$  (*i.e.* far from  
 155 the canopy layer)  $l_v = l_h = \sqrt{\Delta x \Delta y}$  is imposed in this case. The SGS turbulent kinetic energy budget equation is  
 156 expressed as:

$$\frac{\partial e}{\partial t} + \tilde{u}_j \frac{\partial e}{\partial x_j} = -\tau_{ij} \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left( 2v_t \frac{\partial e}{\partial x_j} \right) - C_\epsilon \frac{e^{\frac{3}{2}}}{l_\epsilon} - C_d(z) a_f(z) e \sqrt{\tilde{u}_j \tilde{u}_j} \quad (8)$$

157 The terms on the right hand side correspond respectively to the shear stress production, the turbulent transport, the  
 158 dissipation rate and the SGS energy cascade. This last term, based on the sectional drag coefficient in the horizontal  
 159 direction, depends on the form drag produced by the canopy elements. The formulation used in ARPS was suggested  
 160 by Shaw and Schumann (1992) and is similar to the drag term (4) used in the momentum equation (1) for the hori-  
 161 zontal components.

162

## 163 2.2. Parameterization of the sectional drag coefficient

164 In order to complete and adapt the drag force model (4 and 5) to urban-like canopies, the vertical distribution of  
 165 the sectional drag coefficient  $C_d$  must be defined for different canopy densities and flow regimes. The dependency  
 166 of  $C_d$  on morphological characteristics of the canopy has been investigated from a literature review, mainly based on  
 167 the work of Santiago et al. (2008), Kono et al. (2010), Leonardi and Castro (2010) and Macdonald et al. (2000) for  
 168 staggered arrays of cubes of height  $h$ . It is worth mentioning here that a more sophisticated calibration method of the  
 169 canopy-drag forcing based on multi-objective evolutionary algorithm has recently been proposed by Li et al. (2020)  
 170 for RANS computation and by Wang et al. (2023) for LES. Similarly, the present approach could benefit the mean  
 171 velocity profile modeling techniques such as the analytical model for wind flow in canopies derived by Awol et al.  
 172 (2022). These types of approach are not addressed here and left for future work.

173 Simulations using the  $C_d$  profiles for  $\lambda_p = 16\%$  provided in Santiago et al. (2008), Kono et al. (2010) and Leonardi  
174 and Castro (2010) were performed by Maché (2012). The resulting mean streamwise velocity profiles (not shown)  
175 differed from each other and from experimental data of Macdonald et al. (2000). In particular the simulations failed  
176 to reproduce the variation with height of the velocity vertical gradient (reported for example in Castro 2017). This  
177 is certainly due to the vertical resolution used in our model which is well suited to real city applications but induces  
178 a smoothing of the velocity gradients. The difficulty of using the values directly deduced from obstacle-resolving  
179 methods and the unavailability of  $C_d$  profiles in the lower part of the canopy for densities larger than 20% justify the  
180 need for a specific parameterization of the sectional drag coefficient.

181 The proposed parameterisation is therefore based on the analysis of the dependence of  $C_d$  on the density reported  
182 in the literature with the aim of simulating satisfactory mean velocity profiles in the canopy. In particular the sectional  
183 drag coefficient  $C_d$  should be dependent on the flow regime. For low densities,  $C_d$  is nearly constant which correspond  
184 to an isolated roughness flow regime. The values of  $C_d$  should increase with  $\lambda_p$  (and  $\lambda_f$ ) especially in the lower part  
185 of the canopy, as a consequence of the wake interference flow regime. For greater densities,  $C_d$  should increase in  
186 the upper part of the canopy and decrease again in the lower part which can be interpreted as a consequence of the  
187 skimming flow. The values of  $C_d$  have therefore been adjusted by a guess-and-check method so that the mean velocity  
188 profiles obtained by ARPS agree with profiles from literature for staggered cubes arrays. At the top of the canopy a  
189 very small drag term is added in one to three cells in the vertical in order to avoid numerical instabilities and to smooth  
190 the transition between the canopy and the upper layer. The  $C_d$  profiles for three packing densities are presented in Fig.  
191 1 together with the resulting simulated mean velocity profiles which are compared with wind-tunnel measurements  
192 and CFD results based on obstacle resolving methods. Data from literature used for the comparison is described in  
193 Table 1.

194 A relatively good fit of the streamwise velocity profiles obtained with the model used in the same configuration  
195 as described in Sect. 2.3 is observed for  $\lambda_p = 6.25\%$  and  $44\%$  with the results of Cheng and Porté-Agel (2016),  
196 Macdonald et al. (2000) and Santiago et al. (2008). The profile obtained at  $25\%$  departs slightly from results of  
197 Leonardi and Castro (2010) and Castro et al. (2006), but shows good match with Yang et al. (2016). This could be  
198 explained by their high ratio  $\delta/h \approx 24$ , that draws near our ratio ( $= 100$ ).

### 199 2.3. Numerical details

200 Three-dimensional simulations of the atmospheric flow over homogeneous urban canopies on flat terrain were  
201 performed within  $280h \times 140h \times 140h$  m<sup>3</sup> domains with  $560 \times 280 \times 59$  grid points in the  $x$  (streamwise),  $y$  (spanwise)  
202 and  $z$  (vertical) directions, respectively. The urban canopy height is set to  $h = 10$  m and remains constant over  
203 the simulations, but three packing densities of the urban canopy are considered,  $\lambda_p = \{6.25\%, 25\%, 44\%\}$ , covering  
204 the identified flow regimes (Oke 1988). Here, the packing density is set equal to the frontal area density  $\lambda_f$  as in  
205 experimental studies over staggered arrangement of cubes from Basley et al. (2019); Blackman et al. (2019); Perret  
206 et al. (2019). Horizontal resolution  $\Delta x = \Delta y = 5$  m, vertical resolution of 1 m below  $z = 25$  m and vertical stretching



Table 1 Details of the datasets used for comparison. For CP-A, MCS, YSMM and CCR,  $\delta$  refers to the boundary layer depth. LC's DNS is a channel-flow computation, therefore  $\delta$  refers to the channel half-height. For SCMB's RANS model,  $\delta$  is taken to be the domain height.

Method	Author	Acronym	$\delta/h$
LES	Cheng and Porté-Agel (2016)	CP-A	$\approx 12$
Wind-tunnel	Macdonald et al. (2000)	MCS	10
LES	Yang et al. (2016)	YSMM	$\approx 24$
Wind-tunnel	Castro et al. (2006)	CCR	7.4
DNS	Leonardi and Castro (2010)	LC	8
RANS	Santiago et al. (2008)	SCMB	4

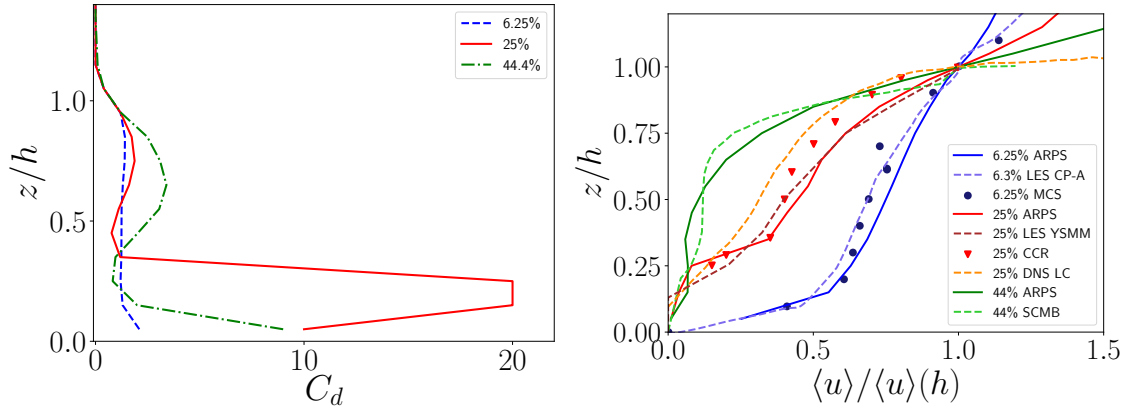


Figure 1 Left : Vertical profiles of  $C_d$  for canopy densities  $\lambda_p = \{6.25\%, 16\%, 25\%, 44\%\}$ . Right : Normalized vertical profiles of the mean streamwise velocity of the present study (solid lines) compared with those of (symbols) wind-tunnel measurements (Macdonald et al. 2000; Castro et al. 2006) and (dashed lines) obstacle resolving methods (Cheng and Porté-Agel 2016; Yang et al. 2016; Leonardi and Castro 2010; Santiago et al. 2008).

207 as a function of a hyperbolic tangent above were used.

208 The lateral boundary conditions are periodic, bottom and top boundary conditions are rigid walls and a 400 m  
209 deep Rayleigh damping layer is set at the top of the computational domain in order to absorb upward propagating  
210 waves and suppress wave reflection from the rigid top boundary. The vertical profiles of the initial velocity field and  
211 base-state potential temperature and specific humidity were computed using a meteorological pre-processor (Penelon  
212 et al. 2001) with a constant vertical profile of potential temperature 300 K, a dry atmosphere and geostrophic wind  
213 of  $12 \text{ m}\cdot\text{s}^{-1}$  aligned with the  $x$ -direction imposed at the top of the boundary layer and in the Rayleigh damping layer.  
214 No Coriolis force is applied in our simulations as this study aims to compare results obtained from a drag-porosity  
215 atmospheric LES model with experimental results obtained from wind tunnel experiments where Coriolis force does  
216 not apply. Moreover, the work mainly concentrates on the flow physics in the lower atmospheric boundary layer, a  
217 region that does not exceed  $z = 300 \text{ m}$  (one third of the ABL depth in the present case), where the veering wind effect  
218 remains negligible.

219 The computation (large) time step was set to  $\Delta t = 0.05\text{s}$ . Since the lowest portion of the ABL is considered in  
220 this study, namely the RSL and the logarithmic region or inertial sublayer, the canopy-based turnover time  $\tau_r = h/u_*$   
221 is used to assess the statistically steady-state of the dynamic flow field, with  $u_*$  the friction velocity. The simulations  
222 with a horizontal spatial grid spacing of  $\Delta x = h/2 = 5 \text{ m}$  were run for 400 000 time steps for the LES, corresponding  
223 to approximately  $600\tau_r$ , and required approximately 7830 core hours of computational time. Moreover, these simu-  
224 lations were initialized with interpolated converged fields from coarser horizontal resolutions ( $\Delta x = h = 10 \text{ m}$ ), run  
225 for  $530\tau_r$ . By using this grid interpolation initialization option, we ensure that flow fields quickly reach a statistically  
226 quasi-steady state : a time convergence study was performed for each simulation, but is not presented here. The choice  
227 of the grid resolution was assessed through a grid convergence study, summarized in appendix A. In order to ensure  
228 statistical convergence, we choose to average flow quantities over an averaging period of  $400\tau_r$ .

229 In the following, results are consistently presented with regards to the three canopy densities :  $\lambda_p = 6.25\%$ ,  $25\%$ ,  
230 and  $44\%$ .

### 231 3. Results and discussion

232 In this section, numerical results obtained with the drag-porosity model for three urban canopy configurations are  
233 analysed and compared with experimental results. For the sake of clarity, the tilde symbol used for LES-resolved  
234 variables is omitted in the following. The streamwise, spanwise and vertical velocity components will be referred as  
235  $u$ ,  $v$  and  $w$  respectively. Each flow variable  $\phi$  is decomposed in a mean and a fluctuating part :

$$\phi = \langle \phi \rangle + \phi' \quad (9)$$

236 where  $\phi$  is the instantaneous variable,  $\langle \phi \rangle$  the (horizontal) space-time average and  $\phi'$  the turbulent fluctuations. The  
237 homogeneous description of the urban canopy employed in the present approach allows for the combination of spatial

Table 2 Characteristics of the boundary layers in the three densities

$\lambda_p$	$u_*$	$\delta/h$	$\delta^+$	$z_0/h$	$d/h$
-	$\text{m s}^{-1}$	-	-	-	-
6.25%	0.281	100	$1.80 \times 10^7$	0.087	0.124
25%	0.310	100	$1.98 \times 10^7$	0.129	0.578
44%	0.284	100	$1.82 \times 10^7$	0.102	0.847

238 averaging in horizontal planes with temporal averaging to improve the statistical convergence.

239 It is worth noting that when the roughness elements are explicitly described, the instantaneous variables (for instance  
240 the velocity field  $u_i$ ) can be decomposed into three components (Coceal et al. 2006) :

$$u_i = \langle \bar{u}_i \rangle_{xy} + u'_i + u''_i \quad (10)$$

241 where  $\bar{u}_i$  is the time average of the variable  $u_i$  at a fixed point,  $\langle u_i \rangle_{xy}$  is the spatial average of  $u_i$  and  $\langle \bar{u}_i \rangle_{xy}$  represents the  
242 time-space average of  $u_i$ . The component  $u'_i = u_i - \bar{u}_i$  is the local turbulent fluctuation relative to  $\bar{u}_i$ , and  $u''_i = \bar{u}_i - \langle \bar{u}_i \rangle_{xy}$   
243 is the spatial variation of  $\bar{u}_i$ . The sum  $u'_i + u''_i$  is the fluctuation from the time-space average value  $\langle \bar{u}_i \rangle_{xy}$ . From  
244 these definitions, the turbulent stress tensor resulting from time-space averaging is the sum of the spatially averaged  
245 Reynolds stress  $\langle \overline{u'_i u'_j} \rangle_{xy}$  and the so-called dispersive stress  $\langle u''_i u''_j \rangle_{xy}$  which represents momentum transport due to  
246 spatial variations in the horizontal directions.

247 Using the drag-porosity approach to model the urban canopy removes spatial heterogeneities in horizontal directions,  
248 leading to  $\langle \bar{u}_i \rangle_{xy} = \bar{u}_i$  ( $\equiv \langle u_i \rangle$  in this work's notation),  $u''_i = 0$  and thus  $\langle u''_i u''_j \rangle_{xy} = 0$ . For this reason, the turbulent  
249 stress is only approximated by the space-averaged Reynolds stress  $\langle \overline{u'_i u'_j} \rangle_{xy}$  ( $\equiv \langle u'_i u'_j \rangle$  in this work's notation) in model-  
250 to-measurement comparisons, and the dispersive stress is never accounted for.

### 251 3.1. Characterisation of the boundary layer

252 The flow Reynolds number  $\delta^+ = \delta u_* / \nu$  is in between  $1.8 \times 10^7$  and  $1.98 \times 10^7$  for the densities considered, where  
253  $\delta$  is the boundary layer height (Table 2). The friction velocity  $u_*$  is estimated from the vertical profile of the Reynolds  
254 shear stress in the constant shear stress region, given by :

$$u_* = \frac{1}{h} \int_h^{2h} \sqrt[4]{\langle u' w' \rangle^2 + \langle v' w' \rangle^2} dz \quad (11)$$

255 The aerodynamic roughness length  $z_0$  and the displacement height  $d$  are derived from the logarithmic law :

$$\langle u \rangle = \frac{u_*}{\kappa} \ln \left( \frac{z-d}{z_0} \right) \quad (12)$$

256 with the von Kármán constant  $\kappa$  set to 0.4.

257 Both aerodynamic parameters  $z_0$  and  $d$  are determined by optimizing the same logarithmic fit of the averaged velocity

258 profiles so as to minimize the root mean square error fitting.

259

260 The present boundary layer shows the existence of an unambiguous log-layer in all investigated cases. This  
261 is shown in Fig. 2 where wall-normal profiles of the averaged streamwise velocity component exhibit a log-law  
262 similarity over more than an order of magnitude.

263 The basic properties of the ABL are reported in Table 2. The logarithmic law (12) is only valid within the so-  
264 called inertial sublayer that extends above the RSL to the height of the atmospheric surface layer. Thus, as per Fig.  
265 2, the RSL extends up to  $(z - d)/z_0 \approx 20$  for the three configurations (*i.e.*  $z/h = 1.86$  for  $\lambda_p = 6.25\%$ ,  $3.16$  for  $25\%$   
266 and  $2.89$  for  $44\%$ ). This is a typical estimate of the RSL height. For example Ismail et al. (2018) found a similar  
267 extent of the RSL up to  $2h - 2.5h$  from their Direct Numerical Simulations of cube-roughened walls, while values  
268 in the order of  $2h$ - $5h$  are also reported in the literature (Raupach et al. 1991). Additionally, the log-law is valid up  
269 to  $(z - d)/z_0 \approx 100$ , which is  $z/h = 8.82$ ,  $13.48$  and  $11.05$  for  $\lambda_p = 6.25\%$ ,  $25\%$  and  $44\%$  respectively. This is in  
270 agreement with the expected values of the atmospheric surface layer depth of about  $10\%$  of the atmospheric boundary  
271 layer height ( $\approx 10h$  in the present case). A particularly good concordance with experimental results from Perret et al.  
272 (2019) of the wall-normal velocity profiles of the three configurations is retained, with similar RSL and log-layer  
273 depths, as well as comparable ABL characteristic parameters.

274 The direct comparison of the aerodynamic parameters with values of previous studies is not straightforward since  
275 large scatter is observed (see e.g. Grimmond and Oke 1999 or Figure 3 in Perret et al. 2019) due to measurement  
276 accuracy or differences in the method employed to estimate  $u_*$  (either from the drag force as in Perret et al. (2019) or  
277 from the turbulent shear stress above the canopy as in eq 11) and  $d$  (as the height where the drag is acting Jackson  
278 1981 or from the log-law fitting of  $z_0$  and  $d$  as in the present study).

279 The value of  $z_0$  matches well the estimates of Perret et al. (2019) and Macdonald et al. (1998) for the two lowest  
280 densities, but is overestimated for the case  $\lambda_p = 44\%$ . However, the change of  $z_0$  with  $\lambda_p$  is comparable for both  
281 results with a larger value of  $z_0$  at  $25\%$ .

282 The value of the displacement length  $d$ , which is typically between  $0 < d < h$  and given in Table 2, shows good  
283 agreement with the range reported by Grimmond and Oke (1999) and Macdonald et al. (2000) for all densities. As  
284 expected and reported in literature, the value of  $d/h$  increases with increasing  $\lambda_p$ .

285 The aerodynamic parameters deduced from the present simulations confirm that the drag approach is able to satisfac-  
286 torily reproduce the bulk influence of the urban canopy on the atmospheric surface layer for various packing density  
287 and flow regimes.

288

289 Profiles of variances, skewnesses and Reynolds stresses of  $u$  and  $w$  are shown in Fig. 3. Variances of the stream-  
290 wise and vertical components show great dependency on packing density, while no clear trend is observed for turbulent  
291 shear stress. Variances and Reynolds shear stress are presented alongside profiles obtained by Perret and Rivet (2018)  
292 based on stereoscopic PIV over staggered arrays of cubes of packing density  $25\%$ . Perret and Rivet (2018) used a

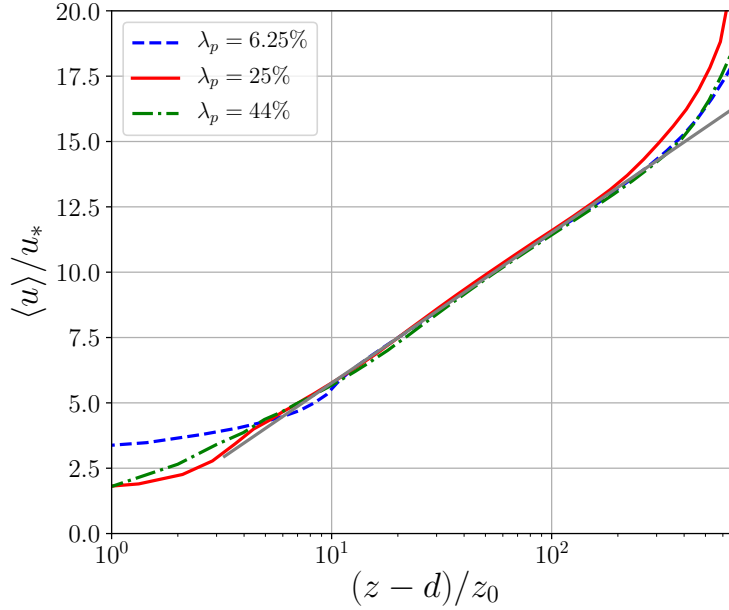


Figure 2 Wall-normal profiles of the mean streamwise velocity component. The solid black line depicts the logarithmic law for the streamwise velocity (equation 12).

293 double average both in time and in the streamwise direction to smooth out the RSL heterogeneity due to the presence  
 294 of the obstacles in the canopy. For this reason, the dispersive stress is not considered and only the Reynolds stresses  
 295 are compared, which show good agreement between numerical and experimental results. Additionally, although the  
 296 values of the variance of the streamwise velocity component observed in the RSL ( $1 < z/h < 2$ ) are consistent with  
 297 Perret and Rivet (2018), the vertical profiles does not show a good match above. This could be due to the large differ-  
 298 ences of ratio  $\delta/h$  (22.7 in Perret and Rivet 2018, 100 in this study).

299 The skewness profile of  $w$  yields strong negative levels within the canopy and inside the RSL. This result, coupled with  
 300 strong positive levels of the skewness profile of  $u$  in the RSL, underlines the predominant contribution of downward  
 301 motions with positive fluctuations  $u'$  to the Reynolds stresses. Above the RSL ( $z/h \leq 2$ ), upward motions become  
 302 predominant, while streamwise skewness levels decrease with height. Further results on the dynamic motions in the  
 303 RSL and logarithmic layer are obtained in 3.2 using a quadrant analysis.

304  
 305 An overall good collapse of velocity profiles with this theoretical log-law and higher order moment profiles with  
 306 literature confirms the well-developed high Reynolds number character of the investigated flows and suggests that the  
 307 coherent turbulent structures obtained with the drag-porosity approach can be compared to the commonly accepted  
 308 view of wall-bounded turbulence. Moreover, this study confirms that the horizontal planes studied in the rest of this  
 309 paper, located at  $z/h = 1.45$  and  $4.45$  are located in the RSL and the log-layer, respectively, for the three investigated  
 310 flows.

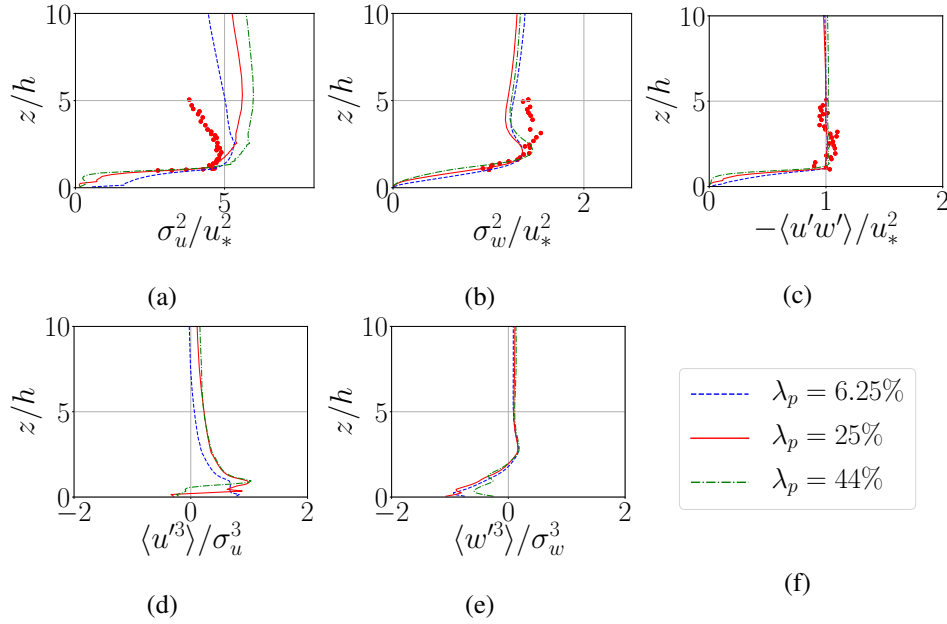


Figure 3 Vertical profiles of variances of (a) streamwise and (b) vertical components; skewnesses of (d) streamwise and (e) vertical components; turbulent flux : (c)  $-\langle u'w' \rangle$ . Red dots represent variances and Reynolds shear stress measured from SPIV of Perret and Rivet (2018) over cubic obstacles of density 25%.

### 3.2. Dynamic motions in the RSL and logarithmic layer

Snapshots of the fluctuating streamwise velocity  $u'/u_*$  in top and side views of the last iteration are discussed here for a qualitative analysis. In the side planes presented in Fig. 4, streamwise velocity fluctuations of the three considered flows have similar appearances, and present eddies of approximately similar sizes and intensity levels. A noticeable difference between the packing densities can however be observed in the near-canopy region where an increase in packing density forces streamwise velocity fluctuations to small values.

Figure 5 compares the top views of fluctuating streamwise velocity inside the canopy ( $z/h = 0.55$ ), in the RSL ( $z/h = 1.45$ ) and in the log-layer ( $z/h = 4.45$ ) for the three investigated flows. In the log-layer of each flow configuration, velocity fluctuations exhibit streaky LSMs, elongated in the streamwise direction with a slightly spanwise meandering effect, characteristic of turbulent boundary layers over smooth planes (Hutchins and Marusic 2007), over vegetation canopies (Watanabe 2004), and over cube canopies (Basley et al. 2018). As in Basley et al. (2019), the coherent structures in the log-layer show no apparent dependency on the canopy configuration. In the RSL,  $u'/u_*$  exhibits anisotropic structures, showing low- and high-speed streaks elongated in the streamwise direction with locations matching well that of the upper LSMs found at  $z/h = 4.45$  : these can be seen as the footprints of the upper LSMs. However it should also be noticed that, in the RSL, smaller and weaker structures (of size of the order of  $h$ ) co-exist and are superimposed onto larger scale structures (of size of the order of  $\delta$ ). This superposition, and the fact that sweeping and ejecting motions highlighted by negative fluctuations of wall-normal shear stress  $u'w'$  (black contour lines in Fig. 5(d)) are mostly generated by LSMs is in good agreement with results obtained from vegetation canopies

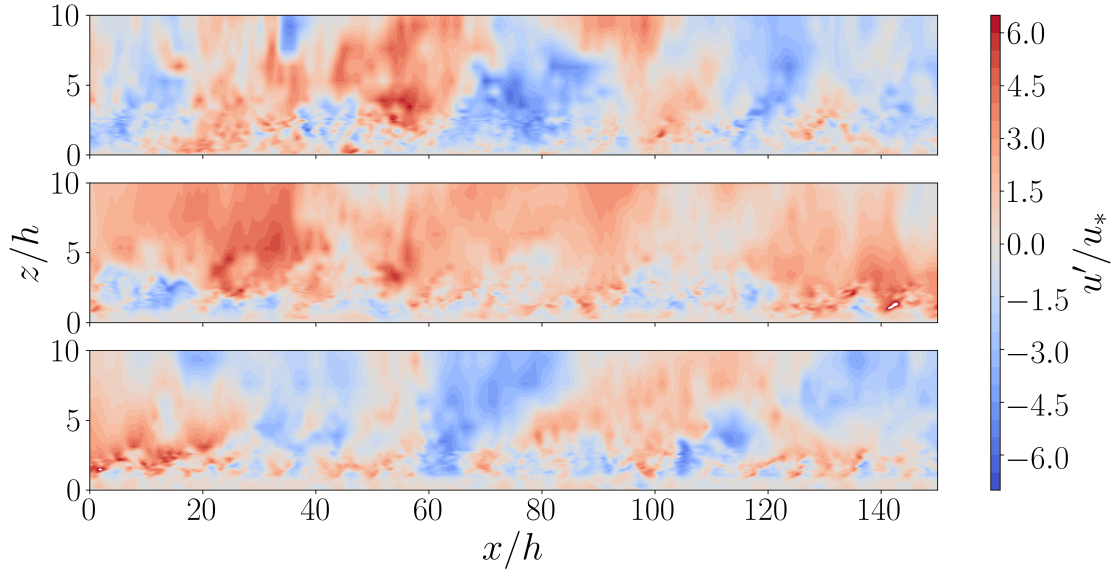


Figure 4 Instantaneous fluctuations of the streamwise velocity component normalised by  $u_*$  for  $\lambda_p = 6.25\%$  (top),  $\lambda_p = 25\%$  (centre) and  $\lambda_p = 44\%$  (bottom) in a  $x - z$  plane.

329 (Raupach et al. 1996, Perret and Patton 2021), and from experimental studies over cube canopies (Basley et al. 2019).  
 330 In the RSL, it appears from Fig. 5 that sweeps, depicted by intense positive fluctuations of streamwise velocity, exist  
 331 as compact strong packets, while ejections, corresponding to intense negative fluctuations of streamwise velocity are  
 332 much rarer and weaker.

333  
 334 Additional information on the relative contribution of ejections (Q2) and sweeps (Q4) events is given by the skew-  
 335 ness profiles in Fig. 3(d, f) and the quadrant analysis showed in Fig. 6. As expected, the contribution of Q1 and Q3  
 336 events to the Reynolds stress is small compared to the more significant contribution of Q2 and Q4 events. The three  
 337 packing densities considered exhibit similar dynamic motions structure within the RSL : an overall larger contribution  
 338 of downward events with positive  $u'$  fluctuations to the Reynolds stress (sweep events) inside the canopy, which peaks  
 339 at  $z/h = 1$ , and a predominant contribution of upward events with negative  $u'$  fluctuations (ejection events) above the  
 340 canopy height with an inversion point located at  $z/h \approx 1.6$  for 6.25%, 1 for 25% and  $\approx 1.2$  for 44%. This inversion  
 341 between Q4 and Q2 events contributions is in good agreement with the work of Coceal et al. (2007) and Castro et al.  
 342 (2006) from DNS and wind tunnel experiments of a staggered cube array respectively. Indeed, they found that close to  
 343 the obstacles sweeps contributed more to the mean shear stress than ejections, while away from the wall the opposite  
 344 was found. Additionally, they located the crossover point between sweep and ejection dominance at  $z/h = 1.25$ . The  
 345 packing density appears to have an impact on the predominating events inside the canopy : while a clear predominance  
 346 of Q4 events is observed throughout the canopy for 6.25%, it is less true for denser canopies where Q2 events even  
 347 appear predominant for  $z/h < 0.5$  for 44%. However, such a feature is difficult to interpret and could be unrealistic.

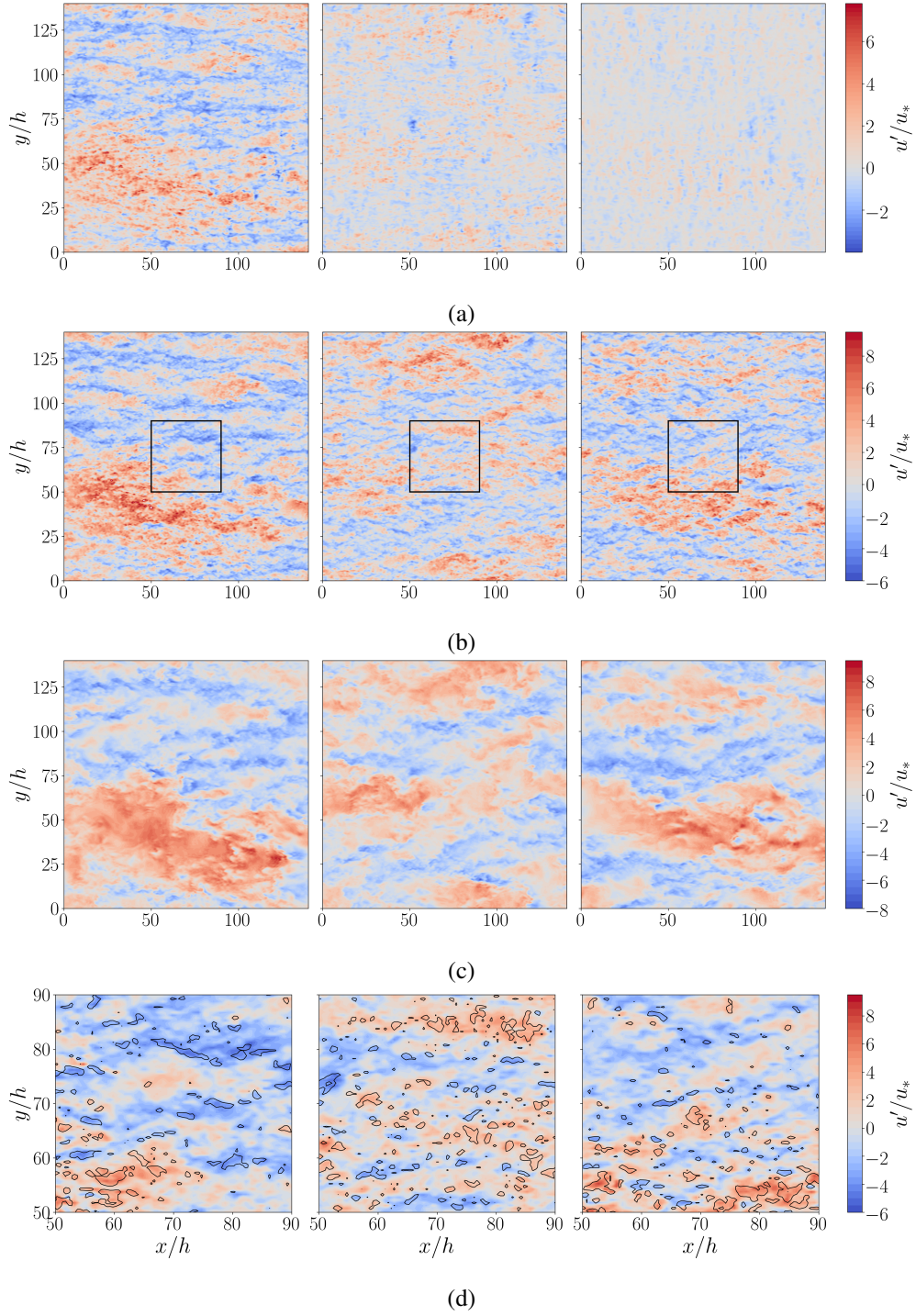


Figure 5 Instantaneous fluctuations of the streamwise velocity component normalised by  $u_*$  for  $\lambda_p = 6.25\%$  (left),  $\lambda_p = 25\%$  (centre) and  $\lambda_p = 44\%$  (right) in a  $x-y$  plane at : (a)  $z/h = 0.55$ , (b)  $z/h = 1.45$ , (c)  $z/h = 4.45$ . Panels (d) are close-up views of the centre of the velocity field at  $z/h = 1.45$  corresponding to the black squares shown in (b). Solid black contour lines depict intense negative levels of wall-normal shear stress  $u'w'$  at level  $-9.12u_*^2$ .



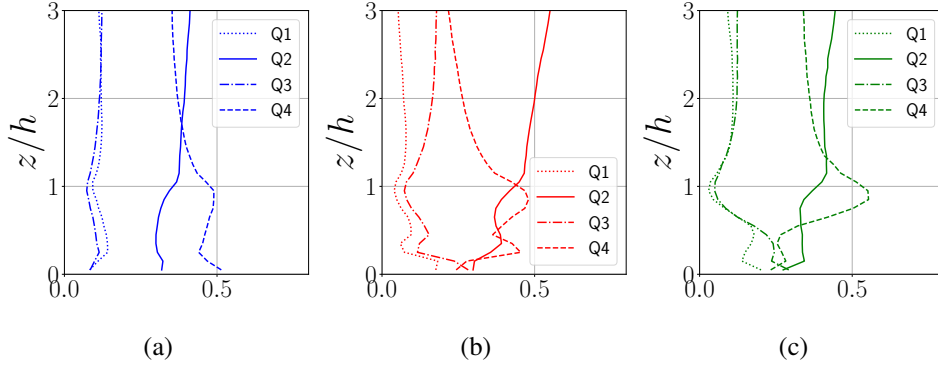


Figure 6 Relative contribution to  $\langle u'w' \rangle$  of events in each quadrant for packing densities of 6.25% (a), 25% (b) and 44% (c).

348

349 Even if this work does not aim at characterizing the turbulent structures and their interactions inside the canopy,  
 350 interesting results can be highlighted from plots in Fig. 5 at  $z/h = 0.55$ . Firstly, a striking effect of the canopy con-  
 351 figuration concerns the difference in momentum levels between the three canopy configurations. Indeed, an isolated  
 352 regime at  $\lambda_p = 6.25\%$  enables more intense velocity fluctuations, while the wake-interference and skimming flow  
 353 regimes ( $\lambda_p = 25\%$  and  $44\%$  respectively) tend to block the development of low- and high-momentum structures.  
 354 Additionally, the footprint of LSMs seen in the RSL extend down to low levels (typically  $z/h = 0.55$ ) in the isolated  
 355 flow regime, as a result of the penetration of the shear layer inside the canopy (in good agreement with Oke 1988).  
 356 However, in denser canopies, the influence of LSMs inside the canopy is weaker, and smaller structures scale with  $h$ .  
 357 Another interesting result from these top views concerns the elongated streak sizes broken down with canopy density,  
 358 and is to be link with Varghese and Durbin (2020) who investigated three flow configurations: a smooth-wall model, a  
 359 rough-wall model (equivalent to the drag-porosity model presented here) and a cube resolved model. By observing a  
 360 break down of streaks inside the canopy for both roughness and cube resolved models compared to the smooth model,  
 361 they conclude that streaks breaking down is not a result of physical obstruction of cubes, but of drag alone. A similar  
 362 result is obtained here when comparing the isolated flow regime (relatively close to a smooth model) with denser  
 363 canopies.

### 364 3.3. Spectral content

365 The qualitative conclusions based on the instantaneous velocity fields in Sect. 3.2 are now further investigated  
 366 through a spectral analysis aiming to identify the structuring length scales of the flow, from the small-scale canopy-  
 367 induced dynamics to the LSMs and VLSMs developing in the logarithmic layer and above respectively. In the fol-  
 368 lowing, one-dimensional spectra are identified with a single subscript, *i.e.*  $S_x$  for an auto-spectra in the  $x$ -direction,  
 369 whereas their two-dimensional counterparts are referred to as  $S$ . All spectra presented in Fig. 7 - 10 are pre-multiplied  
 370 by wavenumbers  $k_{x,y} = 2\pi/\lambda_{x,y}$ .

371

372 Figure 7 shows  $S_x(u, u)$  and  $S_y(u, u)$  the pre-multiplied one dimensional spectra of  $u$  as a function of wall-normal  
 373 distance  $z/\delta$  and streamwise and spanwise wavelength  $\lambda_x$  and  $\lambda_y$ , respectively, as well as the location of the local max-  
 374 imum of the spectra. When considering the evolution of the wavelengths corresponding to the maximum of energy  
 375 with height in the streamwise and spanwise spectra of  $u$ , three distinct regions appear.  
 376 Within the canopy, the location of local maximum is approximately constant with height and correspond to similar  
 377 wavelength for streamwise and spanwise spectra :  $\lambda_{x,y}/h \approx 10$ . This behavior is observed for the three configurations  
 378 and relatively small energetic levels are reached inside the canopy. However a noticeable difference between energetic  
 379 levels inside the canopy can be pointed out : the denser the canopy, the smaller the energetic level.  
 380 Above the canopy, for the RSL and the lower part of the log-layer (*i.e.*  $1 \times 10^{-2} < z/\delta < 5 \times 10^{-2}$ ), the spectrograms  
 381 of  $u$  depict a shift of maximum energy with wall-normal distance  $z/\delta$  towards larger scales. For the streamwise direc-  
 382 tion, this region has to be divided into the RSL ( $1 \times 10^{-2} < z/\delta < 3 \times 10^{-2}$ ), where the wavelengths corresponding  
 383 to the near-canopy structures increase with the wall distance either as  $\lambda_x \propto z^2$ , and the lower part of the log-layer  
 384 ( $3 \times 10^{-2} < z < 5 \times 10^{-2}$ ), where the ridge of maximum energy follows a self-similar tendency  $\lambda_x \propto z$ . For the span-  
 385 wise direction, only the self-similar tendency is retained. These results are in good agreement with both the Townsend  
 386 hypothesis of self-similar structures, which states that self-similar eddies scale with wall-normal distance, and that  
 387 a linear evolution of peak energy production with  $z/\delta$  should be observed, and with Perret and Patton (2021) above  
 388 vegetation canopies, where the  $\lambda \propto z^2$  is observed.  
 389 Well above the canopy, at  $z/\delta > 5 \times 10^{-2}$ , the scales of the most energetic structures are constant with height, and  
 390  $\lambda_{x,y} \propto \delta$ .  
 391 Table 3 summarizes the streamwise and spanwise wavelengths corresponding to the most energetic scales and their  
 392 tendency with height.

393  
 394 If these spectrograms can not obviously exhibit the presence of inner and outer peaks, as it had been found in  
 395 high Reynolds number turbulent boundary layers (Mathis et al. 2009) or under weakly convective conditions (Salesky  
 396 and Anderson 2018), a clear distinction between the evolution of small near-canopy structures and large structures  
 397 with wall distance is showed in Fig. 7, delimited by the black vertical line. Same result was found in wind-tunnel  
 398 studies over staggered cubes (Blackman and Perret 2016), and in LES study over vegetation canopies (Perret and Pat-  
 399 ton 2021). The independence of large structures' wavelengths with wall distance can be interpreted as the signature  
 400 of the Very Large Scale Motions (VLSMs) in the streamwise velocity field whose streamwise extent scales with  $\delta$ .  
 401 Those VLSMs, often reported in the literature (highlighted for high-Reynolds turbulent flows over smooth planes by  
 402 Hutchins and Marusic 2007, and for near-neutral ABL developing over a rough surface representative of an urban  
 403 terrain by Inagaki and Kanda 2010), occupy most of the upper part of the boundary layer.  
 404 To compare characteristic wavelengths of the present study with litterature, the streamwise wavelengths  $\lambda^{max}$  corre-  
 405 sponding to the local maximum of energy extracted from the one-dimensional pre-multiplied auto-spectra  $k_x S_x(u, u)$   
 406 are reported in Fig. 8, with observations from experimental studies on staggered arrays of cubes using LDA measure-

Table 3 Streamwise and spanwise wavelengths  $\lambda_x$  and  $\lambda_y$  corresponding to the most energetic scales of  $u$  in the different regions of the flow for three canopy configurations, normalized by the canopy height  $h$  or the ABL depth  $\delta$

	$z/\delta < 0.01$	$0.01 < z/\delta < 0.03$		$0.03 < z/\delta < 0.05$		$0.05 < z/\delta$	
	$\lambda_{x,y}/h$	$\lambda_x/\delta$	$\lambda_y/\delta$	$\lambda_x/\delta$	$\lambda_y/\delta$	$\lambda_x/\delta$	$\lambda_y/\delta$
6.25%	$\approx 10$	$\propto z^2$	$\propto z$	$\propto z$	$\propto z$	2.8	0.7
25%	$\approx 10$	$\propto z^2$	$\propto z$	$\propto z$	$\propto z$	2.8	0.7
44%	$\approx 10$	$\propto z^2$	$\propto z$	$\propto z$	$\propto z$	2.8	0.7

407 ments of Herpin et al. (2018) for the 25% density, hot-wire measurements of Perret et al. (2019) and SPIV data of  
 408 Basley et al. (2019) for the three canopy densities. This comparison yields remarkably good coherence especially for  
 409 the densest canopies in the RSL and in the lower region of the log-layer ( $(z-d)/\delta < 0.05$ ). In the upper region of the  
 410 log-layer ( $0.05 < (z-d)/\delta < 0.1$ ), important differences are noticed for the three densities, but results collapse above  
 411 the log-layer, where the size of VLSMs remain constant with height at about  $\approx 3\delta$ .

412 However, the wavelengths corresponding to the longitudinal VLSMs may be underestimated by this study, since val-  
 413 ues of  $\lambda_x/\delta = 2.8$  are observed, whereas other studies of neutrally stratified, Coriolis-free ABL turbulence (Fang  
 414 and Porté-Agel 2015; Jacob and Anderson 2017) depict VLSMs streamwise extents that can scale up to  $\approx 20\delta$ . The  
 415 influence of the choice of domain dimensions too small for the computation of the largest eddies is seen here. Indeed,  
 416 the physical domain, of about  $(L_x; L_y) = (2.8\delta, 1.4\delta)$  is not long enough to allow for the development of VLSMs. This  
 417 is why outer peaks are capped at  $\lambda_x/\delta = 2.8$ . For spanwise spectra, the problem of domain size does not seem to  
 418 affect the location of outer peaks, since they all scale with sizes lower than the spanwise extent :  $\lambda_y/\delta = 5 \times 10^{-1}$   
 419 for  $\lambda_p = 6.25\%$ ,  $7 \times 10^{-1}$  for 25% and 1.4 for 44%. It can be important to notice that VLSMs extents obtained for  
 420 sparse canopies yields similar results as Fang and Porté-Agel (2015) for a neutrally-stratified ABL over a smooth  
 421 plane ( $\lambda_y/\delta = 6 \times 10^{-1}$ ).

422  
 423 One can notice the emergence of a crest in streamwise spectra with packing density at the canopy top (for  $1 \leq z/h \leq 2$ ).  
 424 This can be linked with the superposition of small and large scales of turbulent structures inside the canopy and in the  
 425 RSL observed in Fig. 5. Less dense canopies are mostly affected by the characteristics of LSMs developing in the  
 426 log-layer but not so by small scale structures. Conversely, canopy and roughness sub-layers of denser canopies are  
 427 mostly affected by small scales, since there is less penetration of LSMs inside the canopy. This is why a small scale  
 428 (about  $10h$ ) peak emerges in pre-multiplied spectra of 44%.

429  
 430 In Fig. 9, pre-multiplied two-dimensional auto-spectra of  $u$  are considered, in two streamwise-spanwise planes at  
 431  $z/h = 1.45$  and  $z/h = 4.45$  corresponding to the RSL and the log-layer respectively. The capacity to reproduce coher-  
 432 ent turbulent structures observed in the literature with the spectral content is first discussed here within the logarithmic

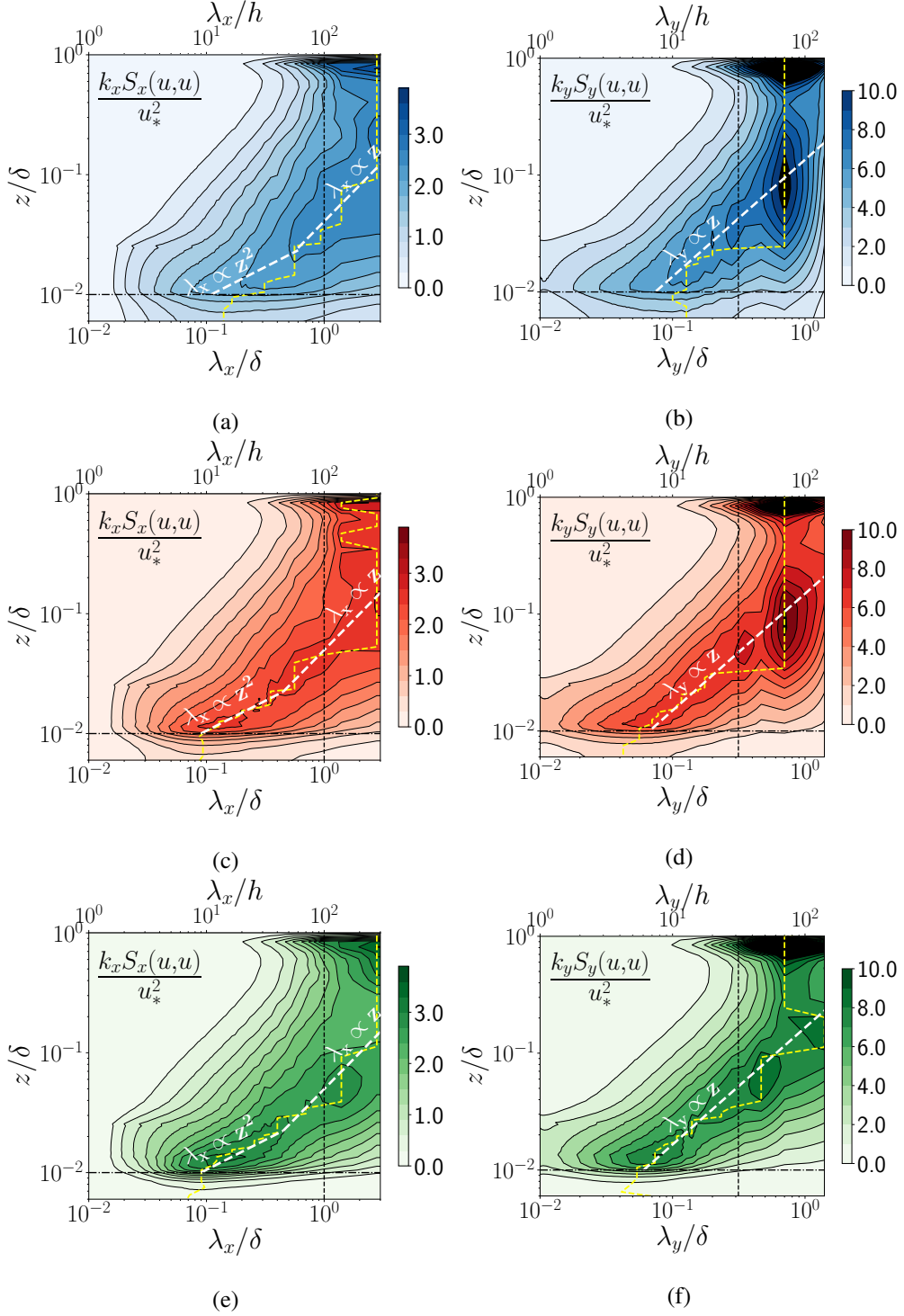


Figure 7 Pre-multiplied spectrograms, plotted as a function of wall-normal distance  $z/\delta$ , streamwise wavelength  $\lambda_x/\delta$  (left) and spanwise wavelength  $\lambda_y/\delta$  (right). Pre-multiplied spectra of  $u$  normalized by  $u_*^2$  for  $\lambda_p = 6.25\%$ ,  $\lambda_p = 25\%$ ,  $\lambda_p = 44\%$  are shown in (a, b), (c, d), and (e, f) respectively. For clarity, spectra are scaled up by a factor of  $10^3$ . The horizontal dash-dotted line corresponds to the canopy top. Oblique dashed white lines corresponds to  $\lambda_{x,y} \propto z$  in (a, b, c, d, e, f) and  $\lambda_x \propto z^2$  in (a, c, e). The yellow dashed line indicates the location of the local maximum of the spectra, and the vertical black dashed line shows the location of the spectral filter ( $\lambda_c/\delta$ )

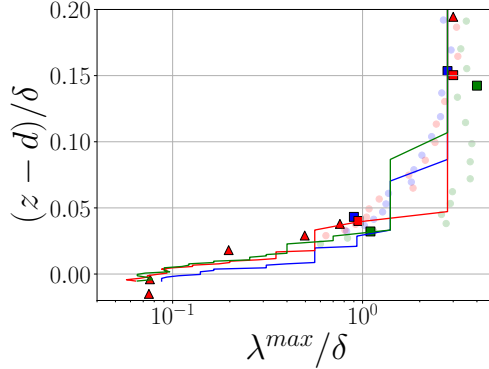


Figure 8 Streamwise wavelengths  $\lambda_x^{max}$  corresponding to the local maximum of energy from the one-dimensional pre-multiplied auto-spectra  $k_x S_x(u, u)$  plotted for 6.25, 25 and 44% (blue, red and green solid lines), against wall distance  $(z - d)/\delta$ . Red triangles are extracted from Herpin et al. (2018), full squares are extracted from the two-dimensional auto-spectra  $k_x k_y S(u, u)$  of Basley et al. (2019), and small light circles are extracted from two-dimensional auto-spectra  $k_x k_y S(u, u)$  of Perret et al. (2019).

433 layer at  $z/h = 4.45$ , hence at the height at which large structures' wavelengths start to become independent with wall  
 434 distance. The first striking result of the spectral content of the streamwise velocity component in the log-layer is the  
 435 independence with regards to the packing density. Therefore, each of the following results are valid for the three con-  
 436 sidered cases. Auto-spectra of  $u$  in the log-layer exhibit the presence of a peak of maximum energy centered around  
 437  $\lambda_x \approx \delta$  and  $\lambda_y \approx 0.4\delta$  relative to the spectral signature of LSMs that shows good coherence with the spectrograms  
 438 of Fig. 7. Analysis of the two-dimensional auto-spectra of  $u$  yields the existence of an increasing anisotropy of the  
 439 structures associated with scales up to  $\lambda_x/\delta = 2.8$ , since the ridge of maximum energy follows a  $\lambda_x \propto \lambda_y^2$  scaling  
 440 law. The result of this trend is an increasing elongation of low- and high-momentum regions as they get wider. This  
 441 anisotropic behavior is in agreement with the findings of Basley et al. (2019) and Jiménez et al. (2004) through a  
 442 study of large-scale dynamics of wall-bounded turbulent flows using DNS. However, at larger scales, Chandran et al.  
 443 (2017), in their study of high Reynolds number boundary layers over smooth walls, predict that energy crest should  
 444 depart from the  $\lambda_x \propto \lambda_y^2$  scaling law to a self-similar law. Due to the limited streamwise extent of the computational  
 445 domain, such a trend can not be confirmed here.

446 Figures 9 (a, c, e) of the pre-multiplied auto-spectra of  $u$  within the RSL ( $z/h = 1.45$ ), show some important dif-  
 447 ferences with characteristics of LSMs developing in the log-layer. The first main difference, in agreement with the  
 448 spectrograms of Fig. 7, is a shift in spectral content towards smaller scales for the three canopies. The same comment  
 449 about the anisotropy of large-scale structures ( $\lambda_x > 0.2\delta$ ), scaling with  $\lambda_x \propto \lambda_y^2$  is still valid in the RSL. For smaller  
 450 structures however, it seems that the ridge of maximum energy is following a self-similar trend, hence leading to the  
 451 coexistence of both non self-similar and self-similar eddies. This coexistence was first observed by Chandran et al.  
 452 (2017) in 2D-spectra of experimental and DNS results of low- and high-Reynolds number turbulent wall-bounded  
 453 flows. For low-Reynolds number flows, the same coexistence is observed (self-similarity of smaller structures, and  
 454  $\lambda_x \propto \lambda_y^2$  scaling law for larger structures), while the opposite is found at higher Reynolds numbers and in the study

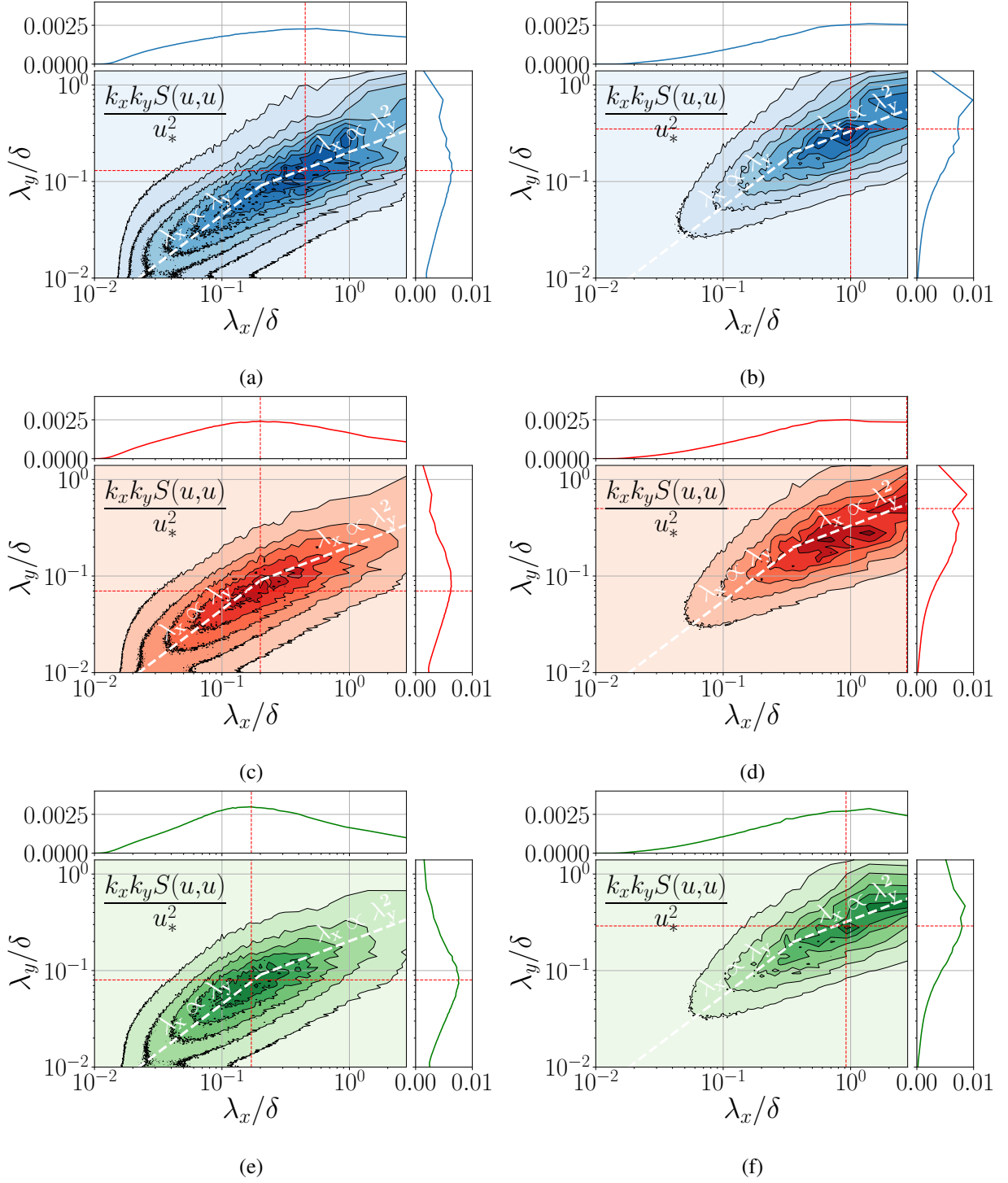


Figure 9 Pre-multiplied auto-spectra in a streamwise-spanwise plane at  $z/h = 1.45$  and  $z/h = 4.45$  for (a, c, e) and (b, d, f) respectively. Pre-multiplied normalized auto-spectra of  $u$ ,  $k_x k_y S(u, u)/u_*^2$  for  $\lambda_p = 6.25\%$ ,  $\lambda_p = 25\%$ ,  $\lambda_p = 44\%$  are shown in (a, b), (c, d), and (e, f) respectively. Oblique dashed white lines corresponds to  $\lambda_x \propto \lambda_y$  and  $\lambda_x \propto \lambda_y^2$ . Red lines intersect at the maximum of the two-dimensional spectra. Contours are shown from 12.5% to 87.5% of the maximum with steps of 12.5%.

455 of Basley et al. (2019). Due to the high-Reynolds number characteristic of our studied flow ( $\delta^+ \approx 2 \times 10^7$ ), same  
 456 anisotropic character should be seen here but the limited streamwise extent of the domain prevents from reproducing  
 457 the self similar trend at larger scales.

458 Figures 9 (a, c, e) also exhibit a monotonic decrease of maximum energy peak with packing density : an isolated  
 459 regime would allow strong penetration of LSMs inside the canopy, thus highlighting a strong predominance of LSMs  
 460 inside the RSL, which manifests in a maximum energy peak occurring at wavelengths close to those observed in the  
 461 log-layer ( $\lambda_x \approx 0.5\delta$ ,  $\lambda_y \approx 0.1\delta$ ). Conversely, an increasing packing density reduces the impact of LSMs footprints in  
 462 the RSL and enhances the contribution of canopy-induced turbulent structures, which results in a shift in maximum  
 463 energy peak towards smaller wavelength ( $\lambda_x = 0.2\delta$ ,  $\lambda_y = 0.07\delta$  for  $\lambda_p = 25\%$ , and  $\lambda_x = 0.15\delta$ ,  $\lambda_y = 0.08\delta$  for  
 464  $\lambda_p = 44\%$ ). This observation is consistent with the “two-scale” behavior brought forward by Reynolds and Cas-  
 465 tro (2008) with two-points correlations of the streamwise velocity component near the top of the canopy and which  
 466 suggest that the large-scale structures existing in the logarithmic layer leave a strong imprint on the flow in the RSL  
 467 and coexist with structures of similar characteristics and energy yet at smaller scales. Hence, a direct impact of the  
 468 canopy density on LSMs in the roughness sublayer is seen here, at the opposite of results from the wind tunnel study  
 469 of Basley et al. (2019) where this superimposition of scales is not brought forward by the 2D-spectra directly, but  
 470 indirectly through the emergence of an unambiguous secondary, canopy-related, peak in one-dimensional streamwise  
 471 spectra  $k_x S_x(v, v)$ .

472  
 473 In order to investigate wall-normal interactions between canopy and RSL, organized mainly in low-velocity up-  
 474 ward ejections and high-velocity downward sweeps, auto-spectra of the wall-normal component  $k_x k_y S(w, w)/u_*^2$  and  
 475 co-spectra  $-k_x k_y S(u, w)/u_*^2$  (with a negative sign to account for the anti-correlation between  $u$  and  $w$ ) are plotted in a  
 476 streamwise-spanwise plane  $z/h = 1.45$  corresponding to the RSL in Fig. 10.

477 Auto-spectra of the wall-normal component are characterized by a range of energetic scales of about  $0.01\delta - 0.06\delta$ , *i.e.*  
 478 of the order of a few  $h$ , in both streamwise and spanwise directions. Larger scales, related to LSMs, have negligible  
 479 energetic levels. It is observed here that canopy packing density has very small impact on energetic wavelengths of  
 480  $w$ , contrary to the slight decreasing tendency found in Basley et al. (2019). However, it should be kept in mind that,  
 481 due to the flatness of peaks in one-dimensional spectra, locating the peak is difficult, and a decreasing wavelength  
 482 tendency with packing density could be hidden. Nonetheless, this highlights that scales related to wall-normal trans-  
 483 port of momentum, and by extension to ejections and sweeps, are associated with canopy interactions, as observed on  
 484 the basis of field observations for urban canopies in Christen et al. (2007). Additionally, a trend following closely the  
 485 scaling law  $\lambda_x \propto \lambda_y$  that puts in evidence the existence of a self-similarity in the wall-normal component is observed  
 486 here, and a near isotropic behavior is also depicted in Fig. 10. Same comment can be made on the pre-multiplied co-  
 487 spectra  $-k_x k_y S(u, w)/u_*^2$ , whose most energetic structures are scaled in between most energetic scales of  $w$  ( $\approx 0.03\delta$ )  
 488 and those of  $u$  ( $\approx 0.1\delta$ ).

489

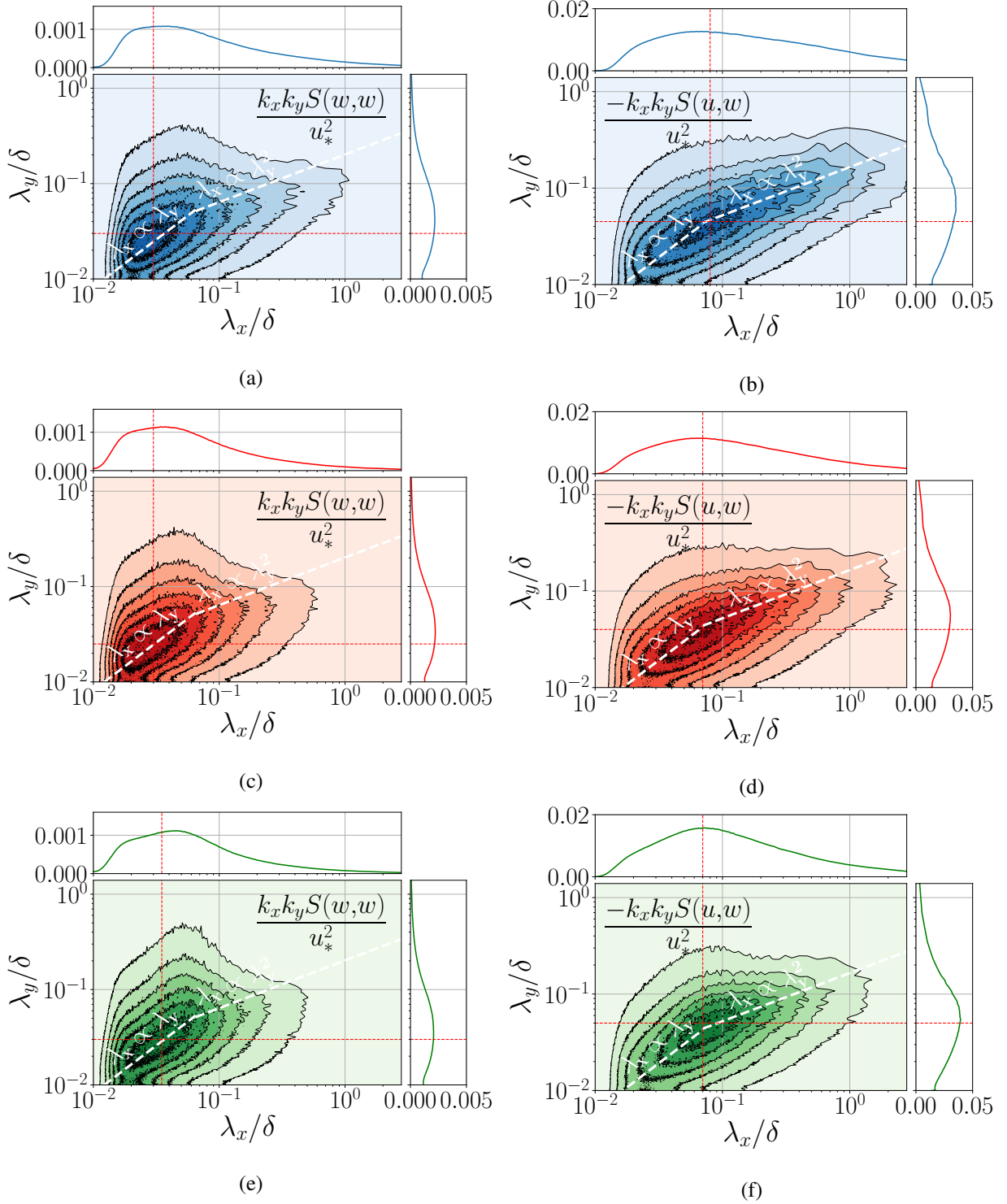


Figure 10 Pre-multiplied auto-spectra of  $w$  and pre-multiplied co-spectra of  $uw$  in a streamwise-spanwise plane at  $z/h = 1.45$  shown in (a, c, e) and (b, d, f) respectively. Pre-multiplied normalized spectra for  $\lambda_p = 6.25\%$ ,  $\lambda_p = 25\%$ ,  $\lambda_p = 44\%$  are shown in (a, b), (c, d), and (e, f) respectively. Oblique dashed white lines corresponds to  $\lambda_x \propto \lambda_y$  and  $\lambda_x \propto \lambda_y^2$ . Red lines intersect at the maximum of the two-dimensional spectra. Contours are shown from 12.5% to 87.5% of the maximum with steps of 12.5%.



490 The spectral analysis presented above reveals that, irrespective of the canopy configuration, upper canopy layers  
 491 are populated with well-known coherent turbulent structures, presenting a good agreement with the literature. The  
 492 present logarithmic layers exhibit elongated low- and high-momentum regions corresponding to streaky LSMs, bear-  
 493 ing anisotropic and self-similar characters that were found in past studies over wall-bounded flows (Jiménez et al.  
 494 2004 and Chandran et al. 2017). A “two-scale” behavior, evidenced by Reynolds and Castro (2008), is particularly  
 495 visible in the roughness sublayer, where long, streaky LSMs superimpose onto smaller, canopy-induced structures,  
 496 organized mainly in low-velocity upward ejections and high-velocity downward sweeps, and which appear to scale  
 497 with a self-similar law close to the canopy. A noticeable impact of the canopy density is observed in the RSL, where  
 498 an increase in packing density generates more drag and intense shear, leading to a predominance of smaller structures.

### 499 3.4. Two-points correlations and inclination angles

500 In order to complement the spectral analysis performed to identify the turbulent structures developing above a  
 501 drag-porosity modelled urban canopy and quantify changes in turbulence spatial structure with packing density, the  
 502 two-point correlation coefficients, their inclination angles and the integral length scales are considered in this section.  
 503 The one-dimensional two-point correlation coefficients of the streamwise velocity  $R_{uu}$  are presented in Fig. 11, and  
 504 two-dimensional contours of  $R_{uu}(dx, z, z_{ref})$  are shown in Fig. 12, where the 2D two-point correlation coefficient of  
 505 the streamwise velocity is calculated as :

$$R_{uu}(dx, z, z_{ref}) = \frac{\langle u'(x, y, z_{ref})u'(x + dx, y, z) \rangle}{\sigma_{u(x,y,z_{ref})}\sigma_{u(x+dx,y,z)}} \quad (13)$$

506 The auto-correlation coefficient  $R_{uu}(dx, z, z_{ref})$  in Fig. 11 exhibit a slow decay with the streamwise separation, as  
 507 an indication of the presence of very long streamwise-elongated structures. The correlation reaches the zero level at  
 508  $dx/\delta = 1.2$  for all heights within the canopy and the RSL for the sparsest canopy. As for the two denser canopies,  
 509 the correlation is still around 0.05 inside the RSL at  $dx/\delta = 1.4$ , and around 0.2 in the log-layer. This increase of the  
 510 LSMs with canopy density is consistent with the results obtained in Sect. 3.3, and the fact that the largest structures  
 511 remain correlated with themselves even at the end of the domain highlights conclusion yielded above concerning the  
 512 limited streamwise extent of the domain, especially for the densest canopy. This is also the reason why negative  
 513 correlation levels for distances far from the reference point, attributed to the presence of long structures, followed by  
 514 similar ones but with opposite negative fluctuations are not observed here, as they are in Fang and Porté-Agel (2015).  
 515 In their study, the dimensions of the computational domain were chosen to be  $(L_x, L_y, L_z) = (32\pi L_z, 4\pi L_z, 1000m)$ ,  
 516 with a horizontal grid of  $\Delta x = \Delta y = 2\pi\Delta z$ , resulting in cells approximately 20 times larger than the cells studied here,  
 517 for relatively similar number of cells. However, Fang and Porté-Agel (2015) performed their LES study over a smooth  
 518 plane in order to investigate VLSMs at high Reynolds number : such an approach is not feasible nor wanted in our  
 519 case, since the objective is to study the influence of wall roughness on dynamics and interaction of coherent structures  
 520 in the lowest layers of the ABL.

521 The changes with packing density of typical scales estimated from the correlation that occur inside and at the canopy

522 top can be noticed in Fig. 11. Sparse canopies are populated with relatively long elongated structures, and correlation  
523 lengths present few changes with increasing wall distance. This is a sign of a “one-scale” behavior, where the im-  
524 print of LSMs remains strong inside the canopy due to isolated obstacles (or in our case, small drag forcing). On the  
525 other hand, correlation lengths are largely reduced for denser canopies, with a streamwise correlation length of about  
526  $dx/\delta = 0.1$  inside the canopy for  $\lambda_p = 44\%$ . This is a sign of a “two-scale” behavior, that results in a decoupling  
527 between flows in the canopy or near-canopy region, and above (*i.e.* in the log-layer).

528  
529 In the spanwise direction, the correlations show an alternating positive-negative trend which is a sign of alternating  
530 low- and high- momentum regions, visible in instantaneous fields in Fig. 5. The scale corresponding to the location of  
531 the first zero-crossing of the correlation coefficient of the streamwise velocity and its evolution with packing density  
532 ( $dy/\delta \approx 0.18$  for 6.25%,  $\approx 0.3$  for 25% and  $\approx 0.4$  for 44%) shows an increase in spanwise width of the streaks with  
533 density ( $\approx 0.32\delta$  for 6.25%,  $\approx 0.4\delta$  for 25% and  $\approx 0.7\delta$  for 44%). Overall, the characteristic spanwise width found  
534 here shows good match with results obtained from LES of wall-bounded flows of Fang and Porté-Agel (2015). An  
535 interesting result is the height at which the alternating positive-negative trend occur for each configuration. Indeed,  
536 if this alternating trend is systematically present in the log-layer for all densities, it appears that the only correlation  
537 function inside the canopy and in the RSL that follows the trend is the one for the sparsest density case. This echoes  
538 the snapshots taken at  $z/h = 1.45$  in Fig. 5, where a large-scale organization develops in the RSL for the sparsest  
539 density, in which the alternation of low- and high-momentum streaks is seen.  
540 The auto-correlation functions of the vertical velocity component  $R_{ww}$  (not shown here) yield similar results as in Sect.  
541 3.3 : a streamwise extension of correlated regions of about  $0.1\delta$ , a spanwise extension of few  $h$ , and the absence of a  
542 clear trend concerning the evolution of correlated structure’ sizes with density.

543  
544 Additional information concerning the shape of coherent structures developing in the RSL and in the log-layer  
545 is given by two-point correlation maps in Fig. 12. As previously observed in wind tunnel and LES (Maché 2012)  
546 simulations,  $R_{uu}(dx, z, z_{ref})$  yields a near-elliptical form in the  $x - z$  plane, with a downwind tilt from the horizontal.  
547 This downwind tilt is estimated using the  $R_{uu}(dx, z, z_{ref}) = 0.4$  iso-contour (highlighted with white iso-contours in Fig.  
548 12), commonly used to approach the calculation of the integral length scale. The inclination angles of  $R_{uu}(dx, z, z_{ref})$ ,  
549 that have been computed for all canopies with the same procedure, are presented in Table 4. An increase in the  
550 inclination angle with density is observed, probably due to the larger wind shear above the canopy, which enables  
551 the inclination of coherent structures. Similar results were observed with the same atmospheric LES solver over  
552 vegetation canopies of various densities by Dupont and Brunet (2008b), in wind-tunnel measurements over cubes  
553 (Reynolds and Castro 2008), and with DNS over resolved cubic obstacles (Coceal et al. 2006).

554 The 0.4 iso-contour shown in Fig. 12 gives clue about the characteristic length scales of coherent eddies, but  
555 Fig. 13 showing the wall-normal evolution of the integral length scale (calculated using the 0.4 criterion) is used  
556 for further discussion. In Fig. 13, integral length scale of the streamwise velocity component are presented in the

Table 4 Inclination angles ( $^\circ$ ) of the spatial 2D two-point correlation function for the streamwise velocity  $R_{uu}(dx, z, z_{ref})$

$z_{ref}/h$	$\lambda_p = 6.25\%$	$\lambda_p = 25\%$	$\lambda_p = 44\%$
1.45	10.82	16.24	17.05
4.45	9.77	12.00	11.87

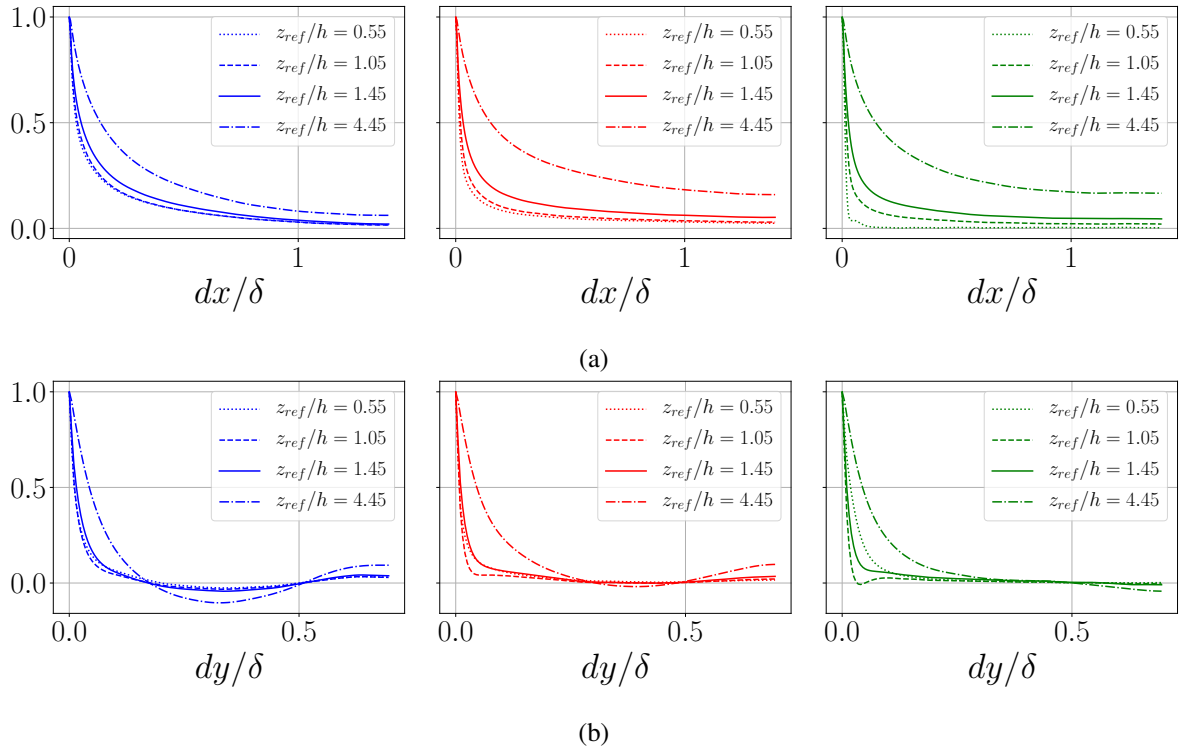


Figure 11 Horizontal variation of the spatial correlation coefficient of the streamwise velocity  $R_{uu}$  in the longitudinal (a) and spanwise (b) directions. The correlation coefficients are evaluated for  $\lambda_p = 6.25\%$  (left),  $25\%$  (center) and  $44\%$  (right).

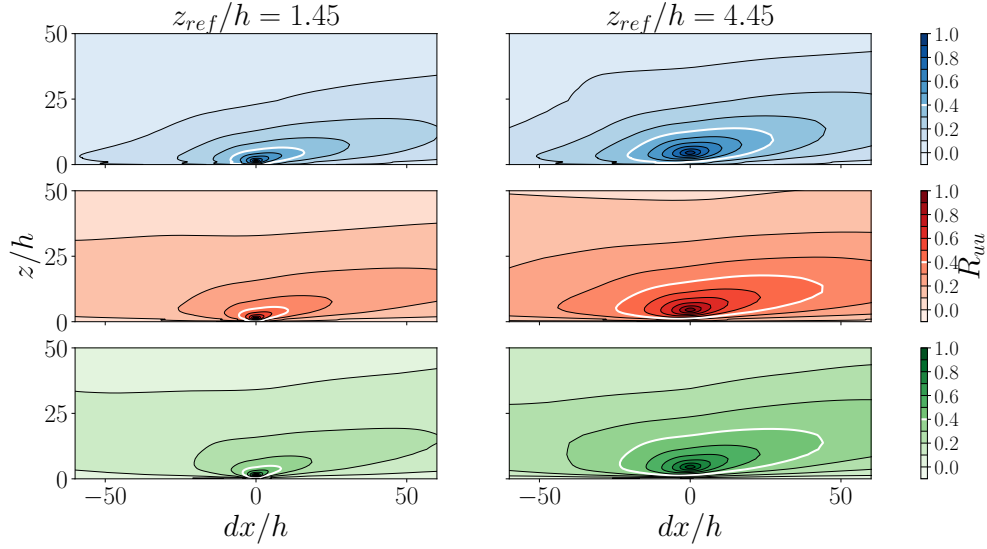


Figure 12 Two-point correlation maps of  $R_{uu}(dx, z, z_{ref})$ , plotted as a function of streamwise ( $dx/h$ ) and vertical ( $dz/h$ ) separations, for  $\lambda_p = 6.25\%$  (top), 25% (middle) and 44% (bottom). Panels are plotted in the RSL (at  $z_{ref}/h = 1.45$ , left) and in the log-layer ( $z_{ref}/h = 4.45$ , right). Iso-levels are shown from 0 to 1 with increments of 0.1. White iso-contours show the  $R_{uu} = 0.4$  iso-level.

557 streamwise ( $\Lambda_{u_x}$ ), the spanwise ( $\Lambda_{u_y}$ ), vertical positive ( $\Lambda_{u_{z+}}$ ) and vertical negative ( $\Lambda_{u_{z-}}$ ) directions. A relatively  
 558 constant evolution of integral length scale with height inside the canopy for the two densest canopies of  $\Lambda_u \approx 3h$  is  
 559 observed at canopy top, and  $\approx 5h$  for  $\lambda_p = 6.25\%$ , which is consistent with Castro et al. (2006) results. As reported in  
 560 the literature,  $\Lambda_{u_y}$ ,  $\Lambda_{u_{z+}}$  and  $\Lambda_{u_{z-}}$  stay relatively constant inside the canopy, and  $\Lambda_{u_x} = \Lambda_{u_z} \approx h$  at canopy top. Above  
 561 the canopy, for  $1 < z/h < 5$  (*i.e.* in the RSL and bottom part of log-layer) a linear increase of integral length scale  
 562 of  $u$  in the  $x$ -direction is observed for all three canopies, with different slopes (steeper as the canopy gets sparser).  
 563 Above  $z/h = 5$ ,  $\Lambda_{u_x}$  largely decreases and differences in levels reached in log-layer are observed from one density to  
 564 another : about  $30h$  for 6.25%,  $45h$  for 25%. The wall-normal evolution is different for the densest canopy, as the  
 565 streamwise integral length reaches very high levels (above  $60h$  at  $z/h = 20$ ) and does not reach a steady value : this is  
 566 a consequence of the limited extent of the computational domain, too small to represent the largest scales in this case.

567 Vertical profiles of integral length scale in the positive and negative vertical direction are displayed in Fig. 13 to  
 568 assess the distance from the roughness at which the attached eddies detached from the wall (distance above which the  
 569 slopes of the profiles of  $\Lambda_{u_{z-}}$  and  $\Lambda_{u_{z+}}$  would coincide). It appears that this feature is observed for the three packing  
 570 densities above  $z/h = 10$ . Hence, these further detached VLMS (referred as type-C eddies in Perry and Marušić  
 571 1995) which contribute to the high-wavenumber motions with length scales not directly related to their distance to the  
 572 canopy start developing at  $z/h = 10$ .

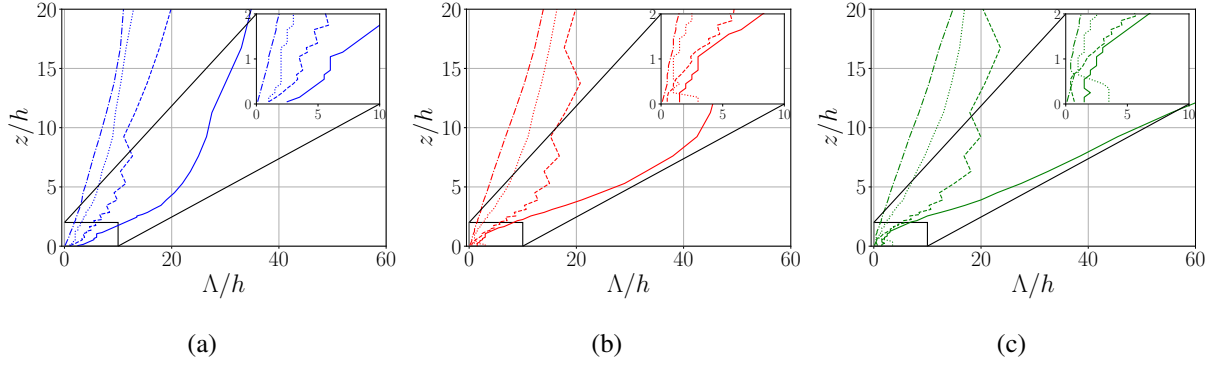


Figure 13 Wall-normal profiles of integral length scales of the streamwise velocity in the streamwise, spanwise, positive vertical and negative vertical directions for  $\lambda_p = 6.25\%$  (a), 25% (b) and 44% (c). Solid lines denote  $\Lambda_{u_x}/h$ , dotted lines are  $\Lambda_{u_y}/h$ , dashed lines  $\Lambda_{u_{z+}}/h$  and dashed-dotted lines  $\Lambda_{u_{z-}}/h$ .

### 573 3.5. Interaction between the most energetic scales

574 Recent studies of high-Reynolds wall-bounded flows have evidenced the existence of an interaction mechanism  
575 that resembles an amplitude modulation process of the most energetic near-wall scales by the most energetic scales  
576 present in the outer region (see Mathis et al. 2009; Blackman and Perret 2016; Salesky and Anderson 2018; Blackman  
577 et al. 2019 among others). The capacity of the drag-porosity model to reproduce this key feature, which suggest  
578 that the near-wall turbulence is triggered by the largest scales of the flow through a phase relationships, is presented  
579 here. The spectral analysis presented in the previous sections clearly showed the distinct signature of both the near-  
580 canopy turbulence and that related to ABL-scales through the presence of two clear peaks in the spectra. Therefore,  
581 following Mathis et al. (2009), the scale separation is performed here via the use of a low-pass filter to extract from the  
582 velocity field the large-scale component  $u_L$  associated with the largest energetic scales and decompose, for instance,  
583 the instantaneous streamwise velocity  $u$  into a space-time averaged mean  $\langle u \rangle$ , large-scale fluctuations  $u'_L$  and small-  
584 scale fluctuations  $u'_S$  :

$$u = \langle u \rangle + u'_L + u'_S \quad (14)$$

585 The cut-off wavelength of the low-pass filter is determined using the pre-multiplied spectrograms of streamwise ve-  
586 locity presented above in Fig. 7, and is chosen so as to separate the most energetic scales present above the logarithmic  
587 layer and those in the near-canopy region. The dotted black lines in Fig. 7 show the location of the cut-off, chosen  
588 to be  $\lambda_c = \delta$  for packing densities of  $\lambda_p = 6.25\%$  and 25%, and  $\lambda_c = 2\delta$  for 44%, which results in the same cut-off  
589 wavelength as in Blackman and Perret (2016) in their experimental results over a staggered cube canopy of  $\lambda_p = 25\%$ .  
590 Basley et al. (2018) showed that the choice of the cut-off wavelength is not a critical point as long as it is located be-  
591 tween the inner and outer spectral peaks. Following this result, no further investigation on the location of the spectral  
592 filter has been addressed here. Mathis et al. (2009) originally proposed using the correlation coefficient between the  
593 large scale component  $u'_L$  and the low-pass filtered envelope of the small scales  $u'_S$ , the so-called amplitude modula-  
594 tion coefficient, as an indicator of the existence and the importance of the amplitude modulation mechanism. They

595 later showed that the cross-correlation  $\langle u'_L u_S'^2 \rangle$ , resulting from the scale-decomposition of the third-order moment  
 596  $\langle u'^3 \rangle = \langle u_L'^3 \rangle + 3\langle u'_L u_S'^2 \rangle + \langle u_L'^2 u_S' \rangle + \langle u_S'^3 \rangle$  was directly related to the degree of amplitude modulation (Mathis et al.  
 597 2011). This latter approach is employed here to quantify the amplitude modulation of the (small) near-canopy scales  
 598 by the (large) ABL scales. The investigation is extended to the three velocity components using the same filtering  
 599 method.

600 The contributions of large- and small-scales to the averaged Reynolds stress components have been investigated  
 601 (not shown here) in order to compare their relative contribution to the total Reynold stresses with the literature results.  
 602 Within the roughness sublayer and in the canopy,  $u_S'$  contributes to the majority of the variances and shear stresses,  
 603 approximately 85%, 95% and 90% to  $\langle u'u' \rangle$ ,  $\langle w'w' \rangle$  and  $\langle u'w' \rangle$ , respectively, for the three configurations at  $z/h = 1.45$ .  
 604 As a comparison, similar results were obtained by Inagaki and Kanda (2010) and Blackman et al. (2019) (60%, 90%  
 605 and 90% respectively). Above the RSL (in the log-layer), the contribution of the large-scale component overtakes that  
 606 of small-scales from  $z/h = 3$  for  $\lambda_p = 6.25\%$  and  $25\%$ , and  $z/h = 4$  for  $44\%$ , for the variance of  $u$  and the shear stress.  
 607 Regarding the variance of  $w$ , the small-scale contribution is consistently more important than the large-scales, over  
 608 the whole RSL and log-layer extent. Overall, no clear trend with  $\lambda_p$  have been observed.

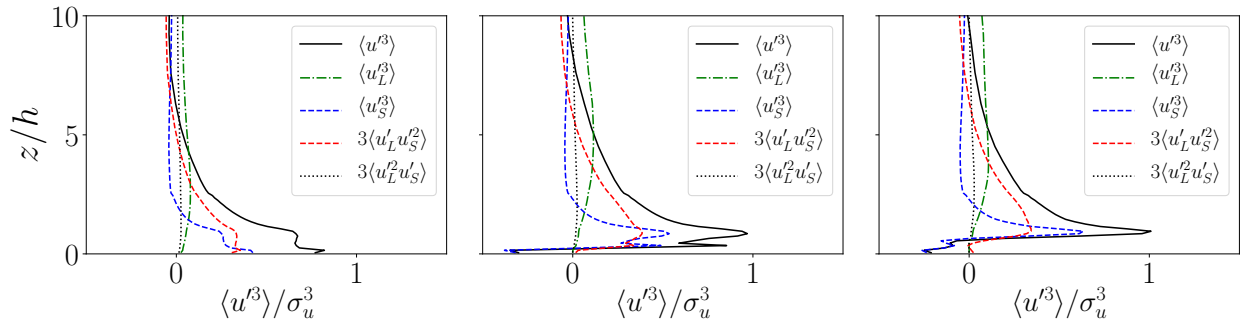


Figure 14 Skewness decomposition of the streamwise velocity  $\langle u'^3 \rangle$  in small-scale skewness  $\langle u_S'^3 \rangle$ , large-scale skewness  $\langle u_L'^3 \rangle$ , and cross-terms  $3\langle u'_L u_S'^2 \rangle$  and  $3\langle u_L'^2 u_S' \rangle$ , for canopy density 6.25% (left), 25% (center) and 44% (right). All components are spatially and temporally averaged, and normalized by  $\sigma_u^3$ .

609 Figure 14 shows the scale-decomposed skewness factor of the streamwise velocity. It appears that, for all canopy  
 610 configurations, the decomposed skewness exhibits a peak at the canopy top ( $z/h = 1$ ) that is most largely due to  
 611 the combined contribution of the small-scale component  $\langle u_S'^3 \rangle$  and the cross-term  $\langle u'_L u_S'^2 \rangle$ . The combination of this  
 612 strongly positive  $u_S'$  skewness and strongly negative  $w$  skewness (shown in Fig. 3) indicates that the predominance of  
 613 intermittent downward moving gusts (sweeps) is mainly influenced by small-scales. Both quantities become negative  
 614 above, at  $z/h \approx 2$  for  $\langle u_S'^3 \rangle$  and above  $6h$  for the cross-term, thus showing similarities with the skewness profile of a  
 615 mixing layer, which agrees with Perret and Kerhervé (2019) and Blackman et al. (2019). The asymmetric character  
 616 of the flow shows relatively high dependence on the packing density : denser canopies produce stronger shear at the  
 617 canopy top resulting in higher skewness values. Alternatively, the large-scale component and the cross-term  $\langle u_L'^2 u_S' \rangle$

618 contribute a negligible amount to the skewness in the RSL, and a non-negligible contribution of  $\langle u_L^3 \rangle$  is observed only  
 619 in the log-layer. The cross-term  $\langle u_L' u_S'^2 \rangle$  represent the non-linear effect of large-scale motions onto smaller scales : its  
 620 non-negligible wall-normal profile could suggest a mechanism such as amplitude modulation, as suggested by Mathis  
 621 et al. (2011).

622 The cross term in the skewness decomposition responsible for the interaction between large- and small-scales  
 623 and its influence on all three velocity components is further investigated in Fig. 15. In particular, the non-linear  
 624 interaction between the large-scale momentum motions and the spanwise ( $\langle u_L' v'^2 \rangle$ ) and the vertical ( $\langle u_L' w'^2 \rangle$ ) non-  
 625 filtered velocity components is compared with  $\langle u_L' u_S'^2 \rangle$ . Similarly as in the literature (Perret and Kerhervé 2019;  
 626 Blackman and Perret 2016), the interaction between large-scales and small-scales in the RSL occurs in a similar  
 627 manner for all flow components.

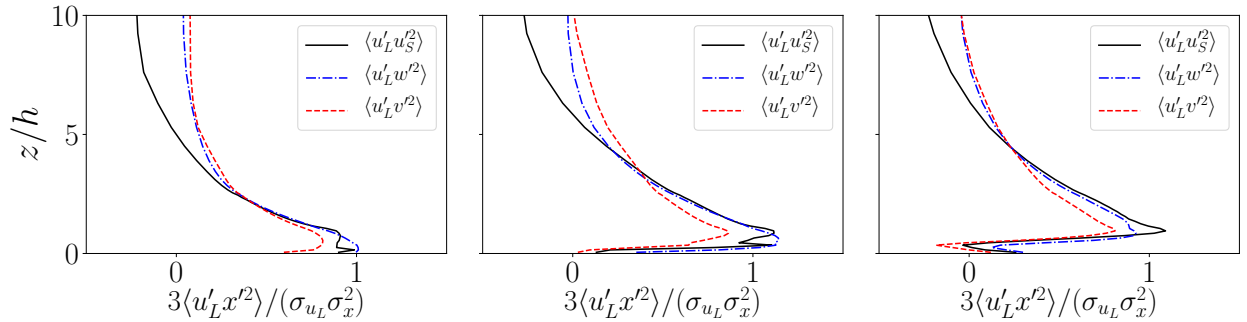


Figure 15 Cross-terms of the skewness decomposition,  $\langle u_L' u_S'^2 \rangle$  (black line),  $\langle u_L' v'^2 \rangle$  (red dashed line) and  $\langle u_L' w'^2 \rangle$  (blue dashed-dotted line). All components are spatially and temporally averaged, and normalized by  $\sigma_{u_L} \sigma_x^2$

#### 628 4. Conclusions

629 The simulations of the atmospheric boundary layer developing over urban canopies modelled using a drag-porosity  
 630 approach and a drag coefficient varying with height served as a basis to assess the capacity of such a rough-wall model  
 631 to reproduce the key features of the spatio-temporal organization of these high Reynolds number flows. Detailed com-  
 632 parisons with the literature of various quantities ranging from the standard one-point statistics to the investigation of  
 633 the existence of the amplitude modulation mechanism of the near-canopy turbulence by the largest scales showed the  
 634 very good performance of the proposed approach to reproduce the characteristics of the urban flows in the well-known  
 635 three typical flow regimes (Grimmond and Oke 1999).

636  
 637 The presence of LSMs and VLSMs was observed qualitatively through snapshots, and quantitatively with spec-  
 638 tral analysis, which revealed that, irrespective of the canopy configuration, upper canopy layers are populated with  
 639 elongated low- and high-momentum regions corresponding to streaky LSMs, bearing anisotropic and self-similar  
 640 characters that were also found in studies over smooth wall-bounded flows (Jiménez et al. 2004 and Chandran et al.

641 2017). Further detached meandering VLSMs were identified above  $z/h = 10$  and occupy most of the upper part of the  
642 boundary layer. The wavelengths of these streaky VLSMs were found to be independent of wall distance and canopy  
643 density, and to scale up to  $2.8\delta$ , with a spanwise width of about  $\approx 0.7\delta$ .

644  
645 The “two-scale” behavior introduced by Reynolds and Castro (2008), was also observed in snapshots with broke-  
646 up streaks in the near-wall region, and in two-dimensional spectra. Indeed, long, streaky LSMs superimpose with  
647 smaller, canopy-induced structures, organized mainly in low-velocity upward ejections and high-velocity downward  
648 sweeps, and which appeared to follow a self-similar evolution with the wall-normal distance close to the canopy, thus  
649 reminiscent of the Townsend (1976) and Perry and Marušić (1995) hypothesis of wall-attached self-similar eddies.

650  
651 A noticeable impact of the canopy density was highlighted in the RSL, where an increase in packing density  
652 generates more mean shear, and leads to a predominance of smaller structures, which was observed particularly in  
653 two-dimensional spectra of  $u$ . Hence, the scales related to ejections and sweeps, responsible for a major part of wall-  
654 normal transport of momentum were proven to show dependence on the canopy pattern, as in Christen et al. (2007).  
655 Additionally, the two-point correlations yielded an important contrast between sparse canopies, where a “one-scale”  
656 behavior occurs, and dense canopies where a decoupling of the flow between the near-canopy and upper regions is  
657 observed.

658  
659 Further investigation was performed to identify the interaction mechanisms that governs flow dynamics within the  
660 RSL. Based on a wavelength spectral filtering method separating the most energetic structures of the ABL from those  
661 generated in the near-canopy region, as suggested by Mathis et al. (2009), a triple decomposition of skewness showed  
662 the major contribution of the small-scale to this quantity in the RSL, and thus to the flow dynamics. This analysis  
663 also objectively confirmed the existence of a non-linear interaction mechanism resembling an amplitude modulation  
664 mechanism of the small scales by the larger scales, that has been qualitatively observed in instantaneous snapshots  
665 of the velocity field, as in previous studies in similar canopy configurations (Blackman and Perret 2016; Basley et al.  
666 2018; Blackman et al. 2019).

667  
668 Overall, this work assesses the good agreement of the model with the literature : the key features of rough-wall  
669 flows are correctly reproduced and the model shows consistent tendency when varying the packing density. The  
670 validity of this approach brings forward the important result, also noted in Varghese and Durbin (2020), that drag  
671 alone is essential for the computation of unsteady near-wall processes within and above the RSL. Hence, the developed  
672 approach could be an essential asset to properly characterize the turbulent flow for wind loading studies on high-rise  
673 building in the urban environment, wich remains a challenge despite research efforts on the inflow generation methods  
674 for large eddy simulation (Thordal et al. 2019). Whilst this model helps to reduce the number of computational cells,  
675 thereby saving some computational costs, a number of important flow characteristics cannot be reproduced, especially



676 within the canopy, such as recirculating regions due to the absence of obstacles, which is why results obtained in this  
677 layer were not analysed in detail in this work. However, this approach has proven to be a powerful tool which, when  
678 coupled with more detailed neighbourhood scale simulations, should provide access to the multi-scale interactions  
679 between the urban boundary layer flow and the flow within the canopy.

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## 683 **Data availability statement**

684 The data that support the findings of this study are available from the corresponding author, Q. Bucquet, upon  
685 reasonable request.

## 686 **Conflict-of-interest statement**

687 All authors certify that they have no affiliations with or involvement in any organization or entity with any financial  
688 interest or non-financial interest in the subject matter or materials discussed in this manuscript.

## 689 **A. Grid convergence study**

690 In order to investigate the effects of grid resolution on results from our LES, we performed several additional  
691 simulations of the  $\lambda_p = 25\%$  case on a  $280h \times 140h \times 140h$  m<sup>3</sup> domain with 4 different horizontal grid resolutions,  
692 ranging from  $\Delta x = \Delta y = 2$ m to 20m. The simulations were configured as described in Sect. 2.3, where  $u_g = 12$   
693 m.s<sup>-1</sup>. Simulations were run for approximately 700 canopy-based turnover times  $\tau_r = h/u_*$  for simulations A and  
694 B, while simulations C and D were initialized with converged fields from coarser resolutions (simulations B and C  
695 respectively), and then run for  $350\tau_r$  and  $150\tau_r$  respectively. Simulation D was not further pursued until  $350\tau_r$  mainly  
696 for calculation costs, and because the statistical steady-state was already reached, according to a time convergence  
697 study not presented here. Averages were calculated over the last  $140\tau_r$  s computed. Parameters of the simulations for  
698 the grid convergence tests can be found in Table A.5.

699  
700 Wall-normal profiles of the main statistics from each grid resolution can be found in Fig. A.1, where the mean  
701 streamwise velocity profile is displayed with the standard deviation of  $u$ ,  $v$  and  $w$ , and their skewnesses. Standard  
702 deviation of  $w$  and skewnesses are relatively insensitive to the grid refinement, except within the canopy region. Mean  
703 streamwise vertical profile appear sensitive to grid resolution, but a grid-resolution independence seems to be reached  
704 for this first-order moment in simulations B, C and D. Profiles of the standard deviation of the streamwise and spanwise

Table A.5 Properties of simulations for grid convergence study

Simulation	Cells number	$\Delta x = \Delta y$	$\Delta t$	$u_*$	$z_0/h$	$d/h$
-	-	m	s	$\text{m s}^{-1}$	-	-
A	(140, 70, 59)	20	0.05	0.368	0.056	0.978
B	(280, 140, 59)	10	0.05	0.381	0.097	0.935
C	(560, 280, 59)	5	0.05	0.346	0.119	0.695
D	(1400, 700, 59)	2	0.03	0.309	0.146	0.549

705 components  $\sigma_u$  and  $\sigma_v$  show the largest variations with grid refinement, grid independence seems to be reached only  
706 for the two finest grids, in simulations C and D. A resolution of  $560 \times 280 \times 59$  (corresponding to simulation C)  
707 is sufficient to make one-point statistics insensitive to grid refinement. The grid sensitivity of auto-spectra of the  
708 streamwise velocity component is shown in Fig. A.2. Both simulations A and B are proven to be inadequate in  
709 computing the energy-producing large scales and the energy cascade following the  $-5/3$  law. Conversely, simulations  
710 C and D show the presence of an inertial range in the spectra and show good agreement with each other in their  
711 overlapping wavelength range. Comparison between simulations C and D shows the clear spectral cut-off effect of the  
712 grid, which is observed for simulation C at scales smaller than  $1.5h$ .

713 This grid-sensitivity analysis showed the best compromise between the computational cost and grid independence  
714 of the statistical characteristics of the simulated flows is obtained with the numerical set-up of simulation C with a  
715 horizontal resolution of  $\Delta x = \Delta y = 5 \text{ m}$  ( $= h/2$ ).

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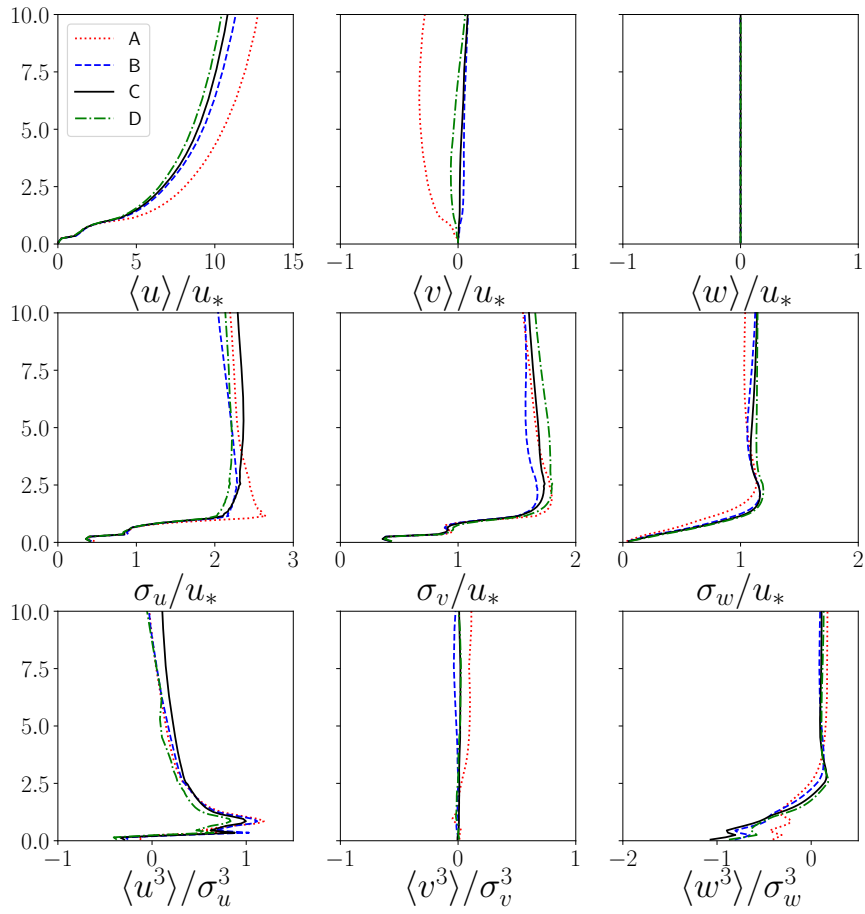


Figure A.1 Convergence of the vertical profiles of the main one-point statistics with grid resolution.

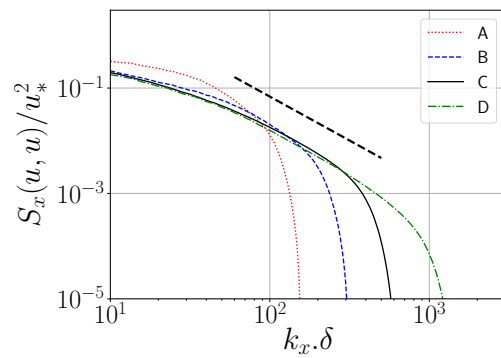


Figure A.2 Convergence of auto-spectra of  $u$  in the  $x$ -direction at  $z/h = 1.45$  with grid resolution. The black dashed line depicts the  $-5/3$  law.

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