

1 **Measurements and computations of flow in an urban street**
2 **system**

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8 **Abstract** We present results from laboratory and computational experiments on the
9 turbulent flow over an array of rectangular blocks modelling a typical, asymmetric
10 urban canopy at various orientations to the approach flow. The work forms part of a
11 larger study on dispersion within such arrays (project DIPLOS) and concentrates on
12 the nature of the mean flow and turbulence fields within the canopy region, recognising
13 that unless the flow field is adequately represented in computational models there
14 is no reason to expect realistic simulations of the nature of the dispersion of pollutants
15 emitted within the canopy. Comparisons between the experimental data and those obtained
16 from both large-eddy simulation (LES) and direct numerical simulation (DNS)
17 are shown and it is concluded that careful use of LES can produce generally excellent
18 agreement with laboratory and DNS results, lending further confidence in the use of
19 LES for such situations. Various crucial issues are discussed and advice offered to
20 both experimentalists and those seeking to compute canopy flows with turbulence
21 resolving models.

22 **Keywords** Direct numerical simulation · Large-eddy simulation · Urban environ-
23 ment · Wind-tunnel modelling

24 **1 Introduction**

25 The use of large-eddy simulation (LES) to compute flow, turbulence and dispersion
26 processes within urban environments is becoming ever more prevalent. This is partly
27 because of continuously increasing computer power available to industry as well as

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in the academic environment, but also because of the recognition that lower order approaches such as Reynolds-averaged Navier-Stokes (RANS) do not adequately capture some of the important physics. Whilst LES has been common at larger scales since Deardorff (1970) and, indeed, forms the basis of most large-scale numerical weather forecasting models (in that processes on scales smaller than the grid are parametrized), it has only within the last fifteen years or so been applied to the range of much smaller scales and arguably greater complexities inherent in flow within urban canopies. In such work, the urban canopy has normally been resolved (to varying degrees of adequacy), rather than modelled in some way as is common in larger-scale (mesoscale) computations. Initially, work concentrated on the flow field itself and was generally aimed at computing cases that had been studied in the laboratory, (e.g. Hanna et al., 2002; Kanda et al., 2004; Xie and Castro, 2006; Smolarkiewicz et al., 2007). More recently studies have included the assessment of scalar dispersion and have also addressed specific field situations (e.g. Xie and Castro, 2009; Moonen et al., 2013). A useful recent review of the use of computational fluid dynamics for dispersion in the urban environment has been provided by Tominaga and Stathopoulos (2013), but the field continues to expand rapidly. (See also the review of Belcher et al., 2013). It is clear that model evaluation is important and this was addressed comprehensively in the European COST action 732 programme (e.g. Schatzmann and Leitl, 2011). However, it is noteworthy that many such attempts (apart from COST732) have concentrated largely on the adequacy of pollutant concentration results and not on the underlying flow field. It is a truism to state that there is little reason to expect dispersion characteristics to be accurate if the underlying turbulent flow field is inadequately predicted, unless there are counterbalancing errors of some kind.

In this paper attention is concentrated on (mostly) the canopy flow field for a neutrally stratified boundary layer developing over an array of rectangular obstacles. Experiments in a large wind tunnel, in which the array is placed within a thick, simulated atmospheric boundary layer (ABL), are reported and compared with corresponding LES data and also with fully resolved direct numerical simulations. The work forms the first stage of a major project, DIPLOS (DIspersion of LOcalised releases in Street networks, www.diplos.org) whose objectives include generating greater understanding of canopy flows so that rapid response modelling approaches based on improved parametrizations can be developed for assessing the transport of potentially hazardous releases in the urban environment. Reporting of the associated concentration fields along with discussion of the extent to which current street-network models adequately predict them will follow in a subsequent paper. Here we address both the nature of the canopy flows for different wind directions and the extent to which LES captures both the mean and the fluctuating flow, using comparisons between the LES data and both laboratory and DNS data. The experimental and numerical approaches are described in Sect.2. This is followed in Sect.3 by a discussion of the upstream and above-canopy flows and then, in Sect.4 and Sect.5, by consideration of the within-canopy flow. Conclusions are summarized in Sect.6.

70 2 Methodologies

71 It has been traditional to use arrays of cubes (height h) in work of this kind be-
72 cause this provides a geometry that leads to efficient DNS and LES computations (in
73 terms of the resources required). The typical case studied has a cube-to-cube spacing
74 equal to the cube size, which results in a rather open array compared with condi-
75 tions in many city centres. The ‘streets’ between the intersections in such arrays are
76 only h in extent and this is inadequate for the establishment of the developed street-
77 canyon flows that form the basis of street-network dispersion models (e.g. Soulhac
78 et al., 2011; Belcher et al., 2015) that are a focus of the current research. Ideally,
79 the street canyons should be long compared to h and of 1:1 or smaller aspect ra-
80 tio (width:height). A compromise solution of $h \times 2h \times h$ blocks with h spacing was
81 adopted, acknowledging both these arguments and the implications in terms of com-
82 puting resource. The latter consideration is all the more significant because an array
83 of at least 18 blocks was needed in the computations to attain results that were essen-
84 tially independent of domain size. Note also that, despite its simplicity, the array is
85 a significant departure from the classical cube array in that it introduces geometrical
86 asymmetry and is thus more typical of real urban areas.

87 Nonetheless, there are many features of real urban areas that are not captured, e.g.
88 sloped roofs of different pitches on different buildings and non-parallel street config-
89 urations. Although complex areas containing such features are occasionally modelled
90 in the laboratory and numerically (e.g. Yassin et al., 2005; Klein and Young, 2011,
91 as examples of specific city areas) and it is known that, for example, roof effects can
92 play an important role in dispersion, our eventual objective is to assess the adequacy
93 of street-network dispersion models and these are not yet available for more complex
94 situations. We can view the array used herein as a stepping stone between classical
95 cube arrays and the more complex situations, but specifically chosen to allow eventual
96 comparisons of dispersion behaviour with that predicted by existing network models.

97 2.1 Laboratory experiments

98 All experiments were conducted in the environmental wind tunnel in the EnFlo lab-
99 oratory at the University of Surrey. This is an open circuit tunnel with a working
100 section that is 20 m long and 3.5×1.5 m in cross-section. The model canopy com-
101 prised a square array of 294 (14×21) $h \times 2h \times h$ rectangular blocks with height $h = 70$
102 mm, mounted on a turntable whose axis of rotation was some 14 m downstream of
103 the test section entrance. The origin of the rectangular coordinate system was set at
104 the turntable (and model) centre, with x in the streamwise direction and z upwards.
105 Figure 1 shows the arrangement for the orientation defined as $\theta = 0^\circ$ – i.e. with the
106 oncoming flow perpendicular to the longer sides of the array obstacles. The array
107 was curtailed at its corners in order to fit the turntable (Fig. 1b) and thus allow ease of
108 rotation to any desired angle. Note that the boundary layer upstream of the array was
109 initiated by a set of five Irwin spires, 1.26 m in height, and developed over surface
110 roughness comprising a staggered array of relatively sparsely distributed thin plates
111 $80 \text{ mm} \times 20 \text{ mm}$ (width and height, respectively), with spacing 240 mm in both x and

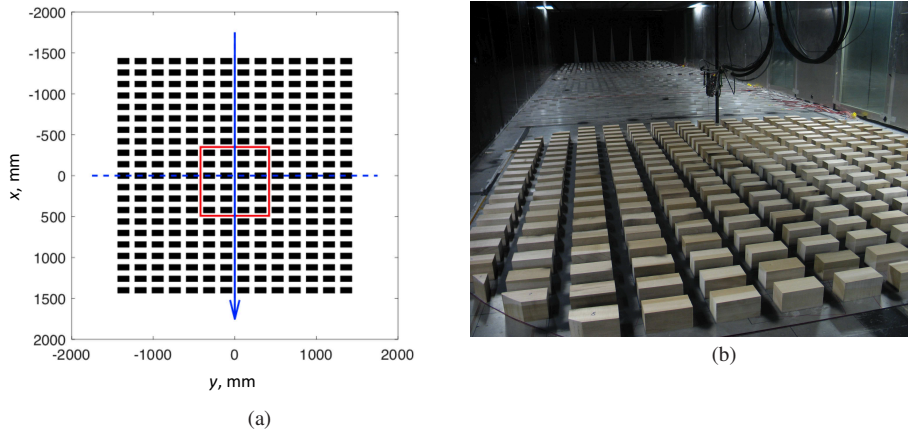


Fig. 1 (a) Plan view of the full array, showing coordinate notation and the domain size used for most of the LES and DNS (outlined in red). (b) Looking upstream in the wind tunnel. The array is in the $\theta = 0^\circ$ orientation with an Laser Doppler Anemometer probe body visible above the array and the upstream spires that help to set the oncoming boundary layer just discernible in the distance.

112 y. The boundary layer at the start of the urban array ($x = -2$ m) was thus about $14h$
 113 in depth and was found to be reasonably homogeneous across the span with no system-
 114 atic spanwise variations. Measured velocities were within $\pm 5\%$ of the spanwise
 115 mean. An internal boundary layer grew from the leading edge of the array, but condi-
 116 tions within the canopy, assessed for example by measurements along a spanwise
 117 street for the $\theta = 0^\circ$ orientation, were essentially independent (i.e. within the experi-
 118 mental uncertainty) of the particular street downwind of the fifth street from the start
 119 of the array. Two reference ultrasonic anemometers mounted downstream of the array
 120 in the tunnel exit ducts were used to ensure that all the experiments were undertaken
 121 at the same freestream velocity in the approach flow (2 m s^{-1}). The Reynolds num-
 122 ber based on obstacle height and the velocity at that height in the upstream bound-
 123 ary layer was about 7,400, or about 830 when based on the friction velocity u_τ (i.e.
 124 $Re_\tau = hu_\tau/\nu$, where ν is the kinematic viscosity). The boundary layer was thus well
 125 within the fully-rough-wall regime.

126 Velocity and turbulence measurements were made using a two-component Dan-
 127 tec Laser Doppler Anemometer (LDA) system with a FibreFlow probe of outside
 128 diameter 27 mm and focal length 160 mm. This provided a measuring volume with
 129 a diameter of 0.074 mm and a length of 1.57 mm. Measurements in the local $U - W$
 130 plane within the street network (i.e. in planes aligned with the streets) were obtained
 131 by use of a small mirror set at 45° beneath a downward pointing probe. The flow
 132 was seeded with micron sized sugar particles at a sufficient level to attain data rates
 133 around 150 Hz. In general, data collection times were 2.5 minutes, selected to control
 134 the standard error in the results. This led to a typical standard error in U of 2%, in
 135 $\overline{u^2}$ of 10% and in $\overline{w^2}$ of 5%, and corresponds to an averaging time of about $200T$,
 136 where T is defined as an eddy turnover time, $T = h/u_\tau$. Our confidence is based on
 137 use of this LDA system over a long period of time, with a range of orientations and

138 geometries (with or without the mirror system). There were many instances of the
139 same variables being measured in different ways, without (for example) probe block-
140 age problems becoming apparent. However, a potential source of significant error in
141 the measurements was due to positioning uncertainty relative to the local buildings
142 and tunnel co-ordinates. For example, an orientation error of 0.1° in the array align-
143 ment to the wind tunnel axis would result in a positioning error of about 2.5 mm
144 relative to the buildings over a 1.5-m lateral traverse (i.e. in the y -direction), assum-
145 ing the traverse itself to be perfectly aligned with the tunnel co-ordinates. There are
146 inevitable imperfections in any wind tunnel and traverse installation and these had
147 particular significance in this case because of the large volume over which results
148 were required. In broad terms, the positional error in any horizontal plane was typ-
149 ically 2 mm. The implications obviously depend on the gradients of flow properties
150 at any given location and resulting uncertainties were greatest in the thin shear layers
151 downstream of the block surfaces (i.e. the side-walls and roof). The consequence of
152 small errors in height relative to the local building roof level were obvious in initial
153 experiments. This particular issue was resolved by use of a small ultrasonic height
154 gauge attached to the traversing arm – in this way local height uncertainties (i.e. rel-
155 ative to the adjacent block) were reduced to about ± 0.5 mm. The results presented
156 here were obtained with this device in use (but see Sect.4 and Fig.11).

157 Further practical issues directly affecting the flow were the accuracy of rotation
158 of the array and its alignment relative to the approach flow. The 0° orientation proved
159 by far the most demanding in these respects as any, albeit small, departure from the
160 ideal set-up generated a small cross-flow in the street network (see Sect.4). Dispersion
161 measurements would then show a plume axis that drifted to one side, as indeed was
162 observed in preliminary experiments that became the motivation for technique and
163 hardware improvements. Ultimately, these resulted in plume axis drift that was less
164 than 1° ; it is hard to see that anything substantially better can be achieved. Finally,
165 it is worth noting that the 45° array orientation case was far less sensitive to these
166 matters, or rather that any consequent effects were far less obvious.

167 2.2 Salient LES details

168 The computations for array orientations of $\theta = 0^\circ$, 45° and 90° were undertaken us-
169 ing the well-known OpenFOAM code, run on the University of Southampton's Iridis4
170 high performance computing system using typically 768 processor cores. Second-
171 order differencing for the convective and diffusive terms was used everywhere and
172 time-stepping employed a second-order backward differencing scheme. Flow in a pla-
173 nar channel whose domain size was $12h \times 12h \times 12h$ was simulated, although some
174 comparative cases were computed with smaller domain sizes (see Sect.4, where it
175 is shown that arrays much smaller were insufficient). The array of (smooth-walled)
176 obstacles was on the bottom (smooth) wall and comprised 24 obstacles – as shown
177 in Fig.1a – with no-slip conditions imposed on all surfaces, whereas at the top of the
178 domain stress-free boundary conditions were imposed. Periodicity was enforced in
179 the other two directions. All the statistics were obtained by averaging over at least
180 $\Delta T = 710T$, after an initial development period of at least $\Delta T = 420T$. Comments

181 about flow convergence will be made in due course. Whilst this approach to comput-
 182 ing rough-wall flows is common, we emphasise that the flow system is fundamentally
 183 different to that in the wind tunnel where, as mentioned above, an internal boundary
 184 layer develops over the array. However, the emphasis in this project is on the nature
 185 of the flow and dispersion within the canopy rather than well above it. One of the
 186 interesting questions we address in Sect.3 is the extent to which this canopy region
 187 (below, say, $z/h = 1.2$) depends on the precise details of the outer boundary layer (or
 188 channel) flow, at least for the range of outer flow conditions modelled in the labora-
 189 tory and by the numerics. It was anticipated that the dependence would not be very
 190 significant and, indeed, this turned out to be the case.

191 A uniform mesh was used (providing formally better numerical accuracy than
 192 more common expanding meshes) with a grid size of $\Delta = h/16$. Because the Reynolds
 193 number was not very high ($Re_\tau \equiv u_\tau h/\nu \simeq 1000$) this was chosen to be near (but
 194 above) the lower end of the range recommended by Xie and Castro (2006) for ade-
 195 quate simulation of urban areas and was a compromise driven by computer time lim-
 196 itations. The mixed time scale sub-grid model proposed by Inagaki et al. (2005) was
 197 used; this circumvents either the (generally rather unsatisfactory) van Driest damp-
 198 ing function near the walls or the difficulties in removing the numerical instabili-
 199 ties which can arise near the walls if, to avoid using damping models, a dynamic
 200 Smagorinsky model is implemented instead. These two difficulties can be particu-
 201 larly severe for cases (like the present) of multi-faceted wall geometry. However,
 202 computations were also performed using the standard Smagorinsky model and only
 203 small differences were observed in the spatially averaged mean velocities and turbu-
 204 lence stresses (less than 2% in mean velocities). Computations using smaller domain
 205 heights ($H = 6h, 8h$ or $10h$) were also undertaken; some representative results will
 206 be shown in Sect.4, confirming the weak effects of outer flow detail on canopy flow
 207 statistics. The flow was maintained by enforcing a fixed axial mass flux.

208 2.3 Salient DNS details

209 Direct numerical simulations were carried out for the same building geometry at
 210 orientations of 0° and 45° . The code was run on the UK national supercomputer,
 211 ARCHER, using typically 240 cores. For detailed descriptions of the development of
 212 the DNS code and the numerical techniques within it, see Yao et al. (2001), and for
 213 examples of its use for urban boundary layer flows, see Coceal et al. (2006, 2007).

214 For the 0° case, the DNS was conducted in a somewhat smaller domain of size
 215 $12h \times 9h \times 8h$, whereas the simulation of the 45° case was carried out in a domain of
 216 size $12h \times 12h \times 12h$ (as used for the LES). In both cases, a uniform grid resolution
 217 of $\Delta = h/32$ was used and the roughness Reynolds number achieved was $Re_\tau = 500$.
 218 This combination of mesh spacing and roughness Reynolds number was previously
 219 verified in similar studies to be adequate for a genuinely resolved DNS (e.g Coceal
 220 et al., 2006, 2007).

221 Periodic boundary conditions in horizontal directions were imposed. No-slip and
 222 impermeability conditions were prescribed at the bottom of the domain and on all
 223 solid surfaces, whereas free-slip boundary conditions were imposed at the domain's

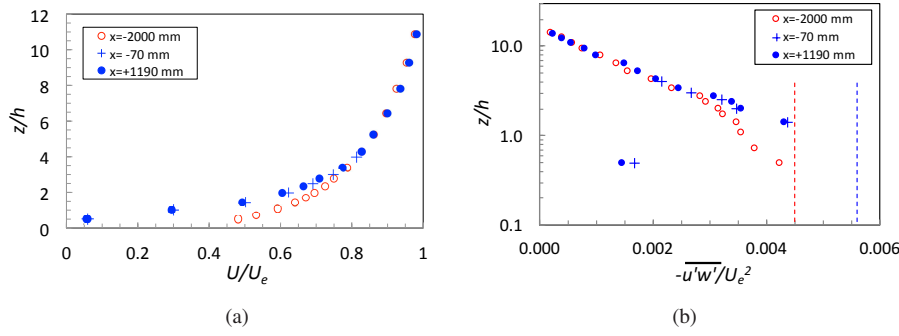


Fig. 2 (a) Mean velocity profiles measured upstream of and over the array and; (b) the corresponding shear-stress profiles. Note that red symbols refer to the upstream boundary layer, blue symbols are profiles taken above the urban array. The vertical dashed lines in (b) indicate the estimated value of u_τ^2/U_e^2 in the two cases.

224 upper boundary. For both orientations, the flow was driven by a constant body force.
 225 The flow Reynolds numbers based on the velocity at the top of the domain, U_e , and
 226 the cube height, h , were typically about $Re_0 = 6,600$ and $Re_{45} = 7,500$ for the 0°
 227 and 45° directions, respectively. By way of comparison, the corresponding Reynolds
 228 numbers in the LES computations were in the range 14,500-16,000 and, in the wind
 229 tunnel experiments, about 9,300.

230 Both simulations were initially spun up until the turbulent flow was fully devel-
 231 oped, which was monitored by the convergence of statistical turbulence measures.
 232 The time step for the simulations was set to $\Delta t = 0.00025T$ in both cases. Statis-
 233 tics were obtained from the converged simulations after a spin-up time of approxi-
 234 mately $\sim 210T$ (0°) and $\sim 380T$ (45°), over averaging periods of $\Delta T_0 \simeq 650T$ and
 235 $\Delta T_{45} \simeq 320T$.

236 3 Results and initial discussion

237 3.1 The upstream boundary layer and its influence downstream

238 For reference purposes the major characteristics of the developed wind-tunnel bound-
 239 ary layer just upstream of the urban array are presented first. Figure 2a shows profiles
 240 of axial mean velocity obtained just upstream of the array and also close to its centre
 241 and within three streets of its downwind edge ($x = -2000$, -70 and 1190 mm,
 242 respectively). Data have been spanwise averaged at each height, using the values
 243 from various profiles taken at different spanwise locations. U is normalized by the
 244 freestream velocity at each location. It is clear that there is very little boundary layer
 245 growth over that fetch (although it is perhaps just noticeable by close inspection of
 246 locations where $U/U_e = 0.95$, say). There is nonetheless a small increase in U_e with
 247 fetch; normalizing by the tunnel reference velocity yields values of 1.013, 1.028 and
 248 1.043 for the three locations. These changes imply a freestream acceleration param-
 249 eter defined by $(v/U_e^2)(dP/dx)$ of below 10^{-6} , normally considered to have a negli-

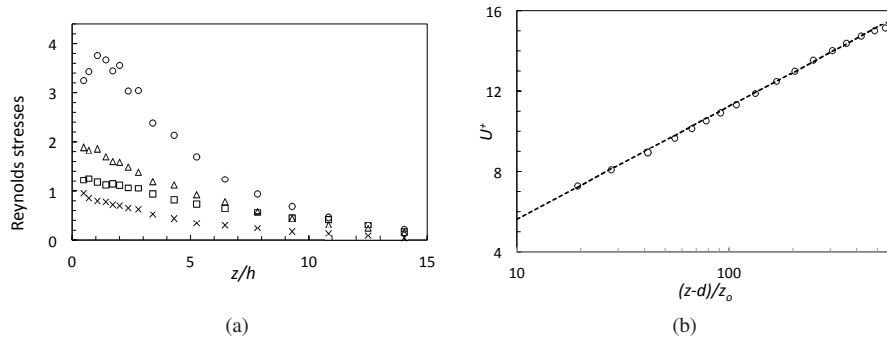


Fig. 3 Wind-tunnel profiles in the upstream boundary layer (near the front edge of the urban array). (a) Reynolds stresses normalized by u_τ^2 ; \circ , $\overline{u^2}^+$; \triangle , $\overline{v^2}^+$; \square , $\overline{w^2}^+$; \times , $\overline{u'w'}^+$. Note that h here remains the urban array height, whereas the height of the upstream roughness elements is $h_u = 0.29h$. (b) Mean velocity data in logarithmic law form. The dashed line is the logarithmic law with $d = 0$, $z_0 = 1.8$ mm ($z_0/h_u = 0.09$) and $\kappa = 0.41$.

250 gible effect on a regular turbulent boundary layer. The changes in U_e largely reflect
 251 the additional mass flux reduction in the inner part of the boundary layer over the
 252 array, evident in Fig.2a. The corresponding shear stress profiles are shown in Fig.2b,
 253 similarly normalized.

254 Note first that above a height of about $3h$ both the mean velocity and the shear
 255 stress profiles at the downstream end of the array are very close to those upstream.
 256 This suggests that the inner boundary layer growing as a result of the change of
 257 surface condition does not reach beyond about $z = 3h$. Above that height, the flow
 258 characteristics are essentially those of the upstream boundary layer. The immediate
 259 implication is that the channel flow LES and DNS data might not be expected to
 260 collapse onto the laboratory data above $z \approx 3h$. We return to this point in due course.

261 Spanwise-averaged centreline values of all the (non-zero) Reynolds stresses at
 262 $x = -2000$ mm are plotted in Fig.3a, all normalized by u_τ^2 . The friction velocity, u_τ ,
 263 was estimated by assuming that the measured (spanwise-averaged) value of $-\overline{uw}$
 264 in the region just above the roughness is lower than u_τ^2 by a factor of 1.3, in accordance
 265 with Cheng and Castro (2002) for a similar (but not identical) canopy morphology.
 266 They showed that for arrays like these, this gave both a better match to the measured
 267 form drag on the elements and a more satisfactory fit of the mean velocity data to the
 268 logarithmic velocity law. In the near-wall region at least, the stresses are all typical for
 269 a naturally grown boundary layer and, overall, they are similar to typical wind-tunnel
 270 simulations of a neutrally stable atmospheric boundary layer. (Close inspection of the
 271 outer region shows differences from a naturally grown layer, but these are immaterial
 272 for the present purposes.) A measure of the adequacy of the estimated friction velocity
 273 ($u_\tau/U_e = 0.067$) is provided by Fig.3b, which shows the mean velocity plotted in
 274 the usual logarithmic law form, $U^+ = \frac{1}{\kappa} \ln \left(\frac{z-d}{z_0} \right)$, and compared with the standard
 275 logarithmic law assuming $\kappa = 0.41$. For the quite sparse roughness of this upstream
 276 boundary layer, $d = 0$ provides a satisfactory fit even beyond what would normally be
 277 expected as the logarithmic law range. This is an indication of the non-natural nature

278 of the outer flow. Note that the top of the roughness is at $z/z_o \approx 11$; depending on the
 279 precise location of the measurement point in the $x-y$ plane one would not necessarily
 280 expect the logarithmic law to be followed much below $z/h_u = 2$ ($z/z_o = 22$), where h_u
 281 is the height of the roughness (20 mm), since such heights would be in the roughness
 282 sublayer region where the flow must be inhomogeneous in both x and y .

283 As noted earlier, over the urban canopy an inner boundary layer grows and we
 284 expect significant changes in the friction velocity and the two logarithmic law param-
 285 eters d and z_o after the upstream edge of the array. This is explored in the following
 286 section, where comparisons with the LES and DNS data are included.

287 3.2 Flow above the urban array

288 The major focus within the DIPLOS project is the canopy region itself (i.e. flow,
 289 turbulence and dispersion in and just above the $z \leq h$ region) but it is of interest
 290 first to consider the flows above the canopy and for various wind directions. Figure
 291 4 presents mean velocity and shear stress profiles for array orientations of $\theta = 0^\circ$,
 292 45° and 90° , comparing laboratory, LES and DNS data. The computed profiles have
 293 been obtained by averaging not only in time but also over the entire computational
 294 domain. They are therefore not expected necessarily to agree with the laboratory data
 295 in the roughness sublayer region (were the flow is homogeneous in neither x nor y),
 296 since the latter data were obtained at specific x, y locations. Although the plan area
 297 density is $\lambda_p = \frac{1}{3}$ independent of wind direction (with λ_p defined in the usual way
 298 by the ratio of the plan area of the elements to the total plan area), intuitively one
 299 would expect the surface drag for the zero degree case to be higher than for the 90°
 300 case. The frontal area density (λ_f , the ratio of the element frontal area ‘seen’ by
 301 the oncoming flow to the total plan area for a repeating unit) is $\frac{1}{3}$ for $\theta = 0^\circ$, i.e.
 302 twice that for $\theta = 90^\circ$, so the former orientation provides a greater flow ‘blockage’.
 303 This larger drag for $\theta = 0^\circ$ is immediately evident: just above the canopy both the
 304 measured and the computed shear stress for $\theta = 90^\circ$ are significantly higher and the
 305 computed mean velocity profile shows a greater velocity deficit. The largest drag,
 306 however, occurs in the $\theta = 45^\circ$ case, for which the near-wall shear stress reaches
 307 values some 13% higher than the 0° values. This is consistent with a slightly higher
 308 λ_f (0.35, cf. 0.33 for 0°) but perhaps more importantly with the fact that there are no
 309 continuous streets in the prevailing wind direction for this particular orientation of
 310 the array.

311 The flow parameters are normalized using the freestream velocity (or the velocity
 312 at the top of the domain in the LES and DNS cases), so do not collapse across the
 313 three orientations. Normalizing using the appropriate friction velocity leads to the
 314 corresponding profiles in Fig.5, from which it is evident that computational data in the
 315 inner region are in as good agreement with experiment as can be expected, especially
 316 given the uncertainty in establishing the friction velocity for the laboratory profiles
 317 (discussed above).

318 Note, first, that above the canopy neither the LES nor the DNS stress profiles
 319 (Fig.5b) collapse exactly onto the expected straight line between (0, 12) and (1, 0).
 320 ($12h = 840$ mm, the domain height). However, they do collapse when the dispersive

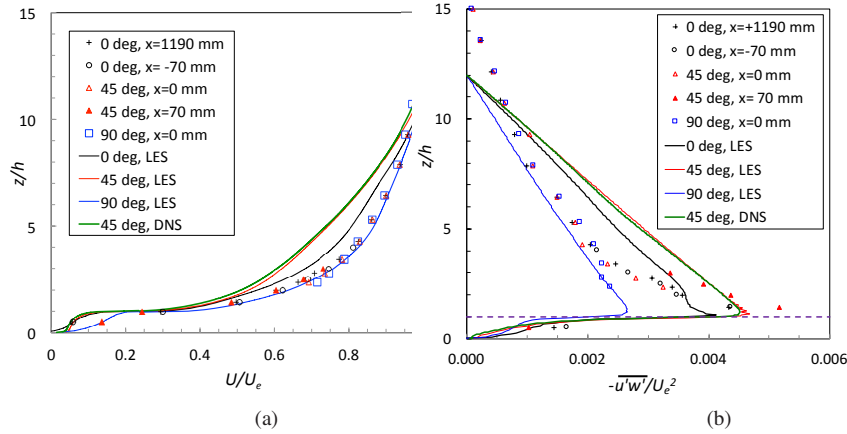


Fig. 4 Mean velocity profiles (a) and shear-stress profiles (b) for the three urban array orientations. Note the location of the top of the canopy, shown as a dashed line at $z/h = 1$ in (b).

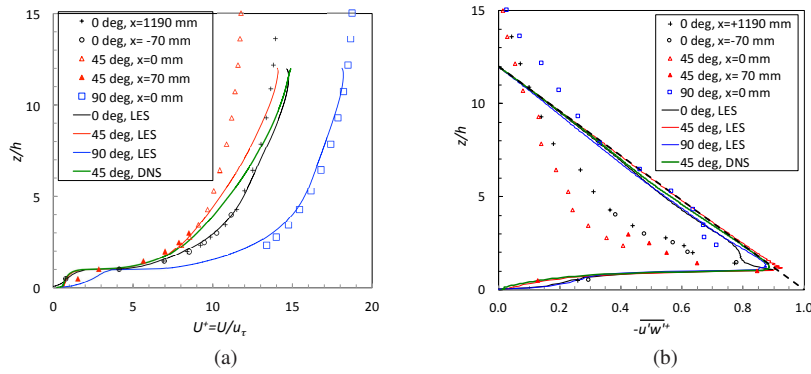


Fig. 5 Data of Fig.4 normalized using wall units. In (b), the dashed straight line joins the points (12,0) and (1,0).

321 shear stresses are added in (not shown) and it was the slope of these total stress lines in
 322 un-normalized form that provided the LES wall stress values. (In these computations
 323 the OpenFoam code was set to maintain a constant mass flux at each time step so,
 324 without time-averaging the computed pressure difference across the two ends of the
 325 channel, this was the most straightforward way to deduce the effectively imposed but
 326 initially unknown wall stress. In the DNS, the known u_τ was forced by the applied,
 327 constant pressure gradient.) The fact that the dispersive stresses (particularly in the
 328 0° and 90° cases) were not exactly zero above, say, $z/h = 2$ could be a result either
 329 of insufficient time averaging or, more likely, the presence of axial rollers in the outer
 330 flow which, as a result of the rather small span, could not move around much in
 331 the spanwise direction. It is interesting, however, that in the 45° case the dispersive
 332 stresses above the canopy were closely zero. The effective span of the domain actually
 333 varies with x in this case and it may be that this (and the effectively variable domain

Case	u^*/U_e	u^*/U_{2h}	Jackson d/h	z_o/h	κ
LAB $\theta = 0^\circ$	0.0748	0.119	0.62	0.086	0.33
LAB $\theta = 45^\circ$	0.0891	0.142	0.59	0.039	0.39
LAB $\theta = 90^\circ$	0.0557	0.078	0.64	0.053	0.265
*LAB $\theta = 90^\circ$	0.0557	0.078	0.86	0.009	0.39
LES $\theta = 0^\circ$	0.0678	0.123	0.62	0.080	0.33
LES $\theta = 45^\circ$	0.071	0.134	0.59	0.077	0.39
DNS $\theta = 45^\circ$	0.067	0.132	0.62	0.082	0.37
LES $\theta = 90^\circ$	0.0550	0.0863	0.64	0.064	0.265

Table 1 Parameter values deduced from laboratory and LES and DNS data. Note that all values for d/h were derived from LES or DNS results, except in the fourth line marked by an asterisk. There, $\kappa = 0.39$ was chosen and d varied to produce the best fit.

length across the span) prevents altogether the appearance of essentially fixed outer layer axial structures. Incidentally, it is worth emphasising that the issue of domain width for channel flow computations and whether or not it is sufficient to allow the possible presence of axial rollers in the outer flow is also important for smooth-wall flows (Fishpool et al., 2009).

Secondly, note that the only DNS data obtained with the $H = 12h$ domain height were for the $\theta = 45^\circ$ case and these data suggest a somewhat lower surface drag, yielding a higher value of U_e/u_τ , most evident in Fig.5a. The LES and DNS profiles in Fig.4a collapse quite well, but the corresponding collapse seen in Fig.4b required the 6% higher value of U_e/u_τ (implied by Fig.5a) for the DNS case. This could be a result of slight inadequacies in the subgrid model used in the LES but it could also be partly explained by the difference in Re_τ , with the DNS value of 500 being about one half that used for the LES. The issue is not important for the present purposes, given our focus on flow variables (normalized by u_τ) in the canopy region, but it will be fully explored in a subsequent paper in which results from computations using various subgrid models and Reynolds numbers will be compared with the fully resolved DNS data.

Thirdly, it is seen that for the 90° case the LES and laboratory mean velocity and shear stress profiles agree quite well over much of the domain. In this case the obstacle array in the wind tunnel provides the least perturbation to the upstream boundary layer. There is a much more significant perturbation in the other two cases, so the wind tunnel profiles over the centre of the array consist more obviously of an inner region in equilibrium with the new surface and whose depth grows with fetch over the array, and an outer region which reflects the characteristics of the upstream surface. The friction velocity consistent with the inner region (increasingly large in the sequence $90^\circ, 0^\circ, 45^\circ$ for a fixed U_e) is thus appropriate for collapsing the LES and laboratory data only in this inner region, consistent with the behaviour shown in the figure.

Fourthly, as explained in Sect.3.1, the laboratory friction velocities were estimated by increasing the shear stresses obtained just above the canopy by the factor 1.3, in accordance with the findings of Cheng and Castro (2002). Table 1 lists the wall stresses for all three orientations, along with corresponding best-fit log-law parameters, which are discussed next. For the fits, the zero-plane displacement height, d was

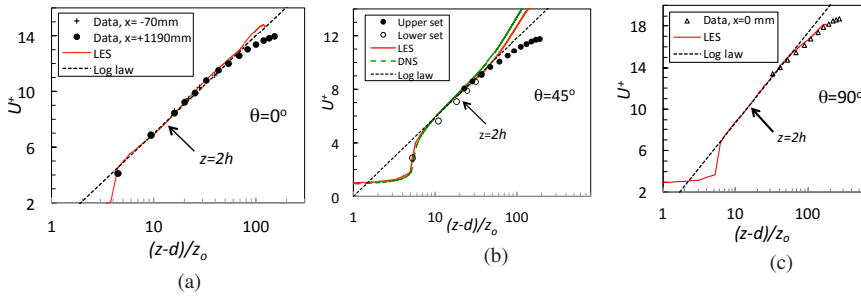


Fig. 6 Mean velocity profiles in log-law form. The logarithmic law parameters (d/h , z_o/h and κ) are given in Table 1. In (b) ‘Upper set’ data refer to those from a probe traverse largely above the canopy height, whereas ‘Lower set’ data are from a separate traverse concentrating on the canopy region only.

367 assumed to be the height at which the surface drag appears to act (Jackson (1981))
 368 and was calculated from the LES and DNS data using the computed pressure field on
 369 the elements and the frictional forces on the surfaces. This leaves only κ and z_o , the
 370 roughness height, as free parameters. The former was chosen to ensure a good match
 371 for the slope in the U vs. $\frac{u_*}{\kappa} \ln[(z-d)/z_o]$ plot and the latter was chosen to ensure
 372 the correct amplitude. For the experimental data, a similar value of d was used but
 373 slightly different values of z_o emerged (compared with those deduced from the LES
 374 data).

375 It is worth noting here that the values of κ in Table 1 are often quite different
 376 to the more classical value of 0.41, which was adequate for fitting the wind tun-
 377 nel’s upstream boundary layer data. The Kármán measure defined by $z^+ \frac{dU^+}{dz^+}$ (where
 378 $z^+ = zu_\tau/\nu$) was not always very closely constant over a reasonable range of z in
 379 the computations; one expects a constant value of $1/\kappa$ for a significant logarithmic
 380 law region. There is therefore some uncertainty in the estimate of z_o and, of course,
 381 different values of κ make a direct link between the value of z_o/h and surface drag
 382 for different cases problematic. A change in κ from 0.33 to 0.4, for example, typi-
 383 cally leads to about a factor of two change in z_o . Note too that there is no reason
 384 to expect the ‘universal’ value of κ to emerge – 0.39 is a recent suggestion for this
 385 by Marusic et al. (2013) – because the ratio δ/h is not really large enough to imply
 386 adequate scale separation between inner and outer layers. An example of the changes
 387 that occur if κ is fixed and d is allowed to vary is included in (the fourth line of)
 388 Table 1 for the $\theta = 90^\circ$ case. Using the method described above this has the lowest
 389 κ (0.265). However, fixing κ at 0.39 (for example) and adjusting d to give the best
 390 fit to the experimental data requires a rather higher d/h and a very much smaller
 391 z_o/h . This latter value is unrealistically small, but fixing d/h as the ‘Jackson value’
 392 yielded quite a poor fit and no region of constant Kármán measure (indeed, values
 393 were quite far from the expected $1/0.39$). We believe our method – given a known u_τ
 394 and known d and adjusting κ to yield the correct logarithmic law slope – is the most
 395 self-consistent.

396 Despite these inevitable uncertainties, there is reasonable agreement between the
 397 laboratory and LES and DNS data and the resulting log-law profiles for each wind

direction are shown in Fig.6. For consistency with the LES, the DNS log-law parameters used in Fig.6b were those used for the corresponding LES case. They differ slightly from the values (shown in Table 1) which produced the best fit to the Kármán measure.

As a final illustration of the boundary layer flow above the canopy, Figs.7a-c shows the turbulence normal stress profiles for the $\theta = 0^\circ$ case. Comparisons for the LES axial stress for different wind directions are shown in Fig.7d. Note first that the experimental profiles of both axial and vertical stresses ($\overline{u'^2}^+$ and $\overline{w'^2}^+$), approximately collapse at different x locations, because they reflect the characteristics of the upstream boundary layer. Only in the inner region would one expect significant differences at different axial locations. Nonetheless, these is a hint that data in the region $1 \leq z/h \leq 4$ at the downstream end of the array ($x = 1190$ mm) are a little higher than further upstream. This is consistent with that downstream part of the flow being more closely in equilibrium with the rougher surface, although it should be borne in mind that stress profiles normalized by the friction velocity are very similar in smooth-wall and rough-wall channels (Leonardi and Castro, 2010). It is notable that the LES axial stress in the outer region (Fig.7a) is significantly larger than the experimental data whilst the differences in the other two components are smaller. This is almost certainly because of the presence of a significantly non-zero dispersive axial stress (not shown), suggesting either that the computation had not yet converged (in time), or perhaps that there are residual large-scale motions in the outer flow, probably as a result of the finite domain span, although if the latter were true one might expect non-zero dispersive stresses in the other two stress components (and there were none). Figure 7d shows that there seems to be a significant dependence on wind direction in the axial stresses in the outer flow. The axial stress is noticeably lower for the 45° wind direction; this is the case that has no residual dispersive stress in the outer region. What is more significant is that the stresses within the canopy ($z/h \leq 1$) are very strongly dependent on wind direction, as expected. It is to this canopy region that we now turn.

4 Flow within the canopy region

Consideration of the flow field within the near-wall region begins by presenting, as examples, the axial and vertical mean velocity ensemble-averaged profiles (for the $\theta = 0^\circ$ case) for a location at the centre of the long street – defined as the street parallel to the longer sides of the array obstacles. In this section velocities oriented in the street directions are used - so U_s , V_s are velocities normal and parallel, respectively, to the long side of the obstacles. Only for $\theta = 0^\circ$ does $U_s = U$, $V_s = V$. There is very good collapse between laboratory, LES and DNS profiles of U_s^+ obtained using the $12h$ domain length (Fig.8a), despite the different domain heights and widths used; the agreement continues all the way to $z = 6h$ and $8h$ (not shown). However, a profile given by an LES run using a domain size significantly smaller in plan ($6h \times 6h$) differs from the others once $z/h > 1$. This must be a result of the narrower (and perhaps also the shorter) domain used and the effect is further illustrated by the V_s^+ profiles seen in Fig.8b. For this array orientation (0°) and symmetrical location of the pro-

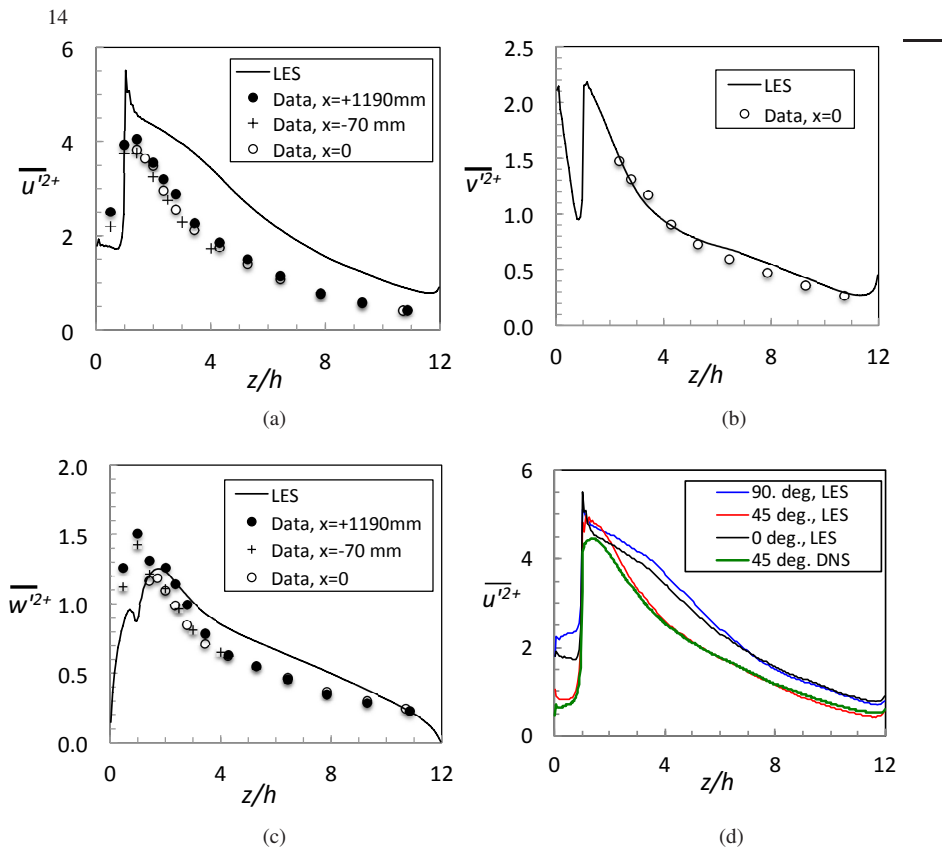


Fig. 7 Normalized stress profiles for $\theta = 0^\circ$. (a) axial; (b) spanwise; (c) vertical stresses. (d) Comparison of the LES axial stress for the three wind directions.

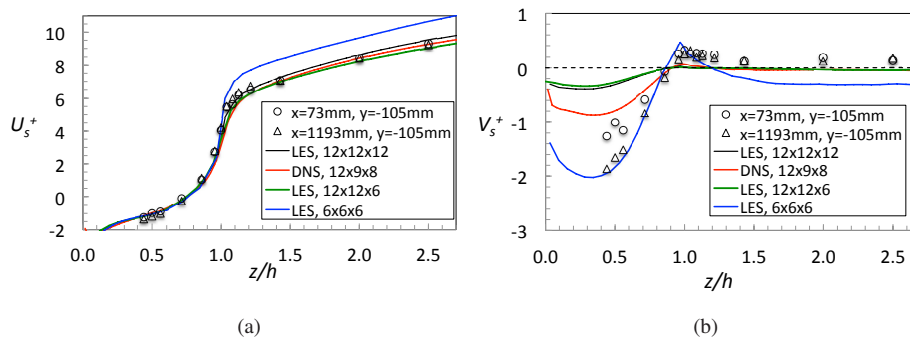


Fig. 8 Ensemble-averaged mean velocity profiles at the long-street centreline for $\theta = 0^\circ$; (a) U_s^+ , (b) V_s^+ .

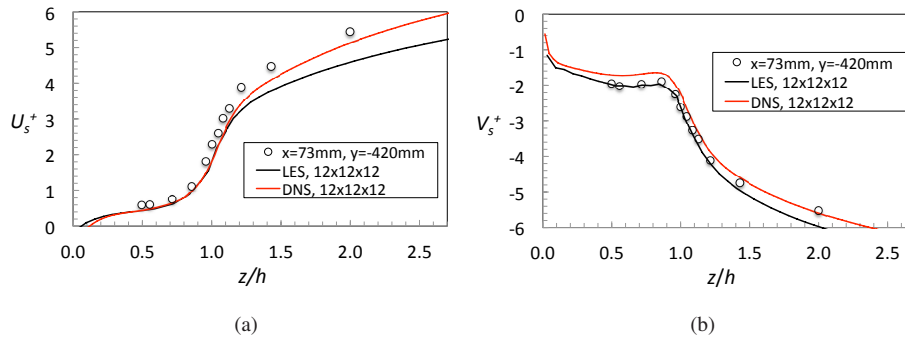


Fig. 9 Ensemble-averaged mean velocity profiles in street coordinates at the centre of the street intersection for $\theta = 45^\circ$; (a): U_s^+ , (b): V_s^+ .

441 files with respect to the array blocks, one would anticipate a zero spanwise velocity
 442 at all heights. However, this is not found in either the experiments or the numerical
 443 computations and is indicative of a small, but definitely non-zero difference between
 444 the canopy and the domain-top mean velocity orientations. Note that the fact that the
 445 V profiles within the canopy in Fig.8b are all the same sign is in one sense a coinci-
 446 dence (whether the y -coordinate is at $+90^\circ$ or -90° to the x -direction in either the
 447 laboratory or the numerical domain is completely arbitrary).

448 Some limited tests in the laboratory showed that the unexpected non-zero V could
 449 be removed by an appropriate rotation of the array (by only a degree or two). In the
 450 numerical computations, the periodic conditions imposed at the spanwise extents of
 451 the domain allow non-zero V and it appears that too small a domain width can pro-
 452 mote a spanwise flow through the entire domain height, leading to an effective (and
 453 small) ‘free-stream’ flow angle at the domain top. By far the largest flow angle at the
 454 top (about 1.3°) is given by the LES on the $6h \times 6h \times 6h$ domain and it appears that
 455 this is sufficient to trigger much larger flow angles within the canopy – not dissimilar,
 456 in fact, to the laboratory values (see Fig.8b). At $z/h = 0.5$, for example, this smaller
 457 domain LES run yields a flow angle in excess of 45° relative to the sides of the ob-
 458 stacles (rather than the expected value of zero, but note that at that height the axial
 459 velocity is very small). This whole issue emphasises the care that is required in un-
 460 dertaking either laboratory or numerical experiments for these types of canopies. The
 461 reason for the non-zero spanwise flow at all heights in the computations is unclear; it
 462 may be that the total drag (and thus energy expended) is lowest for a small non-zero
 463 flow angle and the computation naturally picks out this lowest-energy flow. Further
 464 work would be needed before a definitive answer could be identified. It is possible
 465 that the zero-degree case is somewhat pathological, as it is presumably relatively easy
 466 for the flow to ‘switch’ intermittently to conditions either side of a strictly symmet-
 467 ric state. Imposing a small non-zero wind angle could thus arguably provide a more
 468 satisfactory case for comparing wind tunnel and numerical models.

469 Similar examples of velocity profiles are shown in figure 9 for $\theta = 45^\circ$. Again,
 470 these are ensemble averaged across all corresponding street locations in the whole

471 domain. In this case, the LES and DNS results for U_s diverge for $z/h > 1$, consistent
 472 with the plan-averaged profiles shown in Fig.6b and with a small difference in the
 473 computed flow angles at the top of the domain (not shown). It is not clear why this
 474 difference occurs. Because of the array asymmetry with respect to the flow at $\theta = 45^\circ$
 475 this topology is expected to yield a non-zero lateral force in a numerical channel flow
 476 computation (i.e. a force at 90° to the drag force, defining the latter as the array force
 477 in line with the flow direction at the top of the domain). As Claus et al. (2012) discuss,
 478 such a non-zero force implies that the mean flow angle at the top of the domain must
 479 be slightly inclined to the forcing direction. Our results are qualitatively consistent
 480 with the earlier Claus et al. (2012) findings in that a non-zero angle shift occurs up to
 481 some height above the array, although the deviation appears more pronounced in the
 482 case of the LES (extending all the way to the top of the domain).

483 We turn now to profiles along the streets (rather than vertically through them),
 484 focussing first on street centrelines near $z/h = 0.5$. Figure 10 shows some examples
 485 of these and includes mean velocity (U_s) and the two major shear stresses along the
 486 y street for the $\theta = 0^\circ$ array orientation (Figs.10a,c,e) and both mean velocities and
 487 $\overline{u'_s v'_s}^+$ for the $\theta = 45^\circ$ orientation. As before, the computed data are ensemble aver-
 488 aged across all available parallel streets in the domain. Consider first the $\theta = 0^\circ$ case
 489 (the left hand column of Fig.10). Note that the mean velocity shown (U^+ , Fig.10a)
 490 is the velocity across the street, i.e. in the free-stream flow direction. So behind the
 491 blocks the velocity is negative and relatively small, whereas between them it is posi-
 492 tive and much larger as the flow tends to sweep down the x streets in the main flow
 493 direction. There is good agreement between the laboratory and computational data,
 494 not just for this mean velocity (Fig.10a) but also for the Reynolds shear stresses
 495 (Figs.10c,e). The fact that the local magnitudes of the $\overline{u'_s v'_s}^+$ stress (Fig.10e), which
 496 on average across the span must be zero by symmetry, is about the same as those of
 497 the other dominant stress (Fig.10c) is a clear indication of the very three-dimensional
 498 and anisotropic nature of the turbulence field within the canopy. It is significant that
 499 the domain height, which is different for all three computation profiles, again has no
 500 significant effect on the canopy flow.

501 The level of agreement for the $\theta = 45^\circ$ case is not quite so good, although it is
 502 interesting that the shear stress data shown in Fig.10f all collapse reasonably well.
 503 On the other hand, whilst the computed LES and DNS mean velocities are satisfy-
 504 ingly close (Figs.10b,d, and all obtained with a $12h$ domain height), there is a rather
 505 larger level of disagreement between them and the laboratory data. However, the latter
 506 are quite scattered and clearly vary significantly depending which axial (x) location
 507 was chosen for the traverse. For this array orientation the experiments to obtain data
 508 within the canopy were particularly tricky, but special care was taken over the final
 509 traverses at $x/h = 1$ ($x = 70$ mm), with data taken at much closer intervals in an at-
 510 tempt to identify the various peaks and troughs. These data are satisfyingly close to
 511 the computed profiles.

512 Very accurate vertical positioning of the LDA probe is not crucial at $z/h = 0.5$,
 513 where the slopes in vertical profiles of the flow variables are not large. At $z/h = 1$,
 514 however, slopes *are* large (see Fig.8a for example) so that lateral profiles taken near
 515 this ‘roof-top’ position are subject to rather more uncertainty when compared with

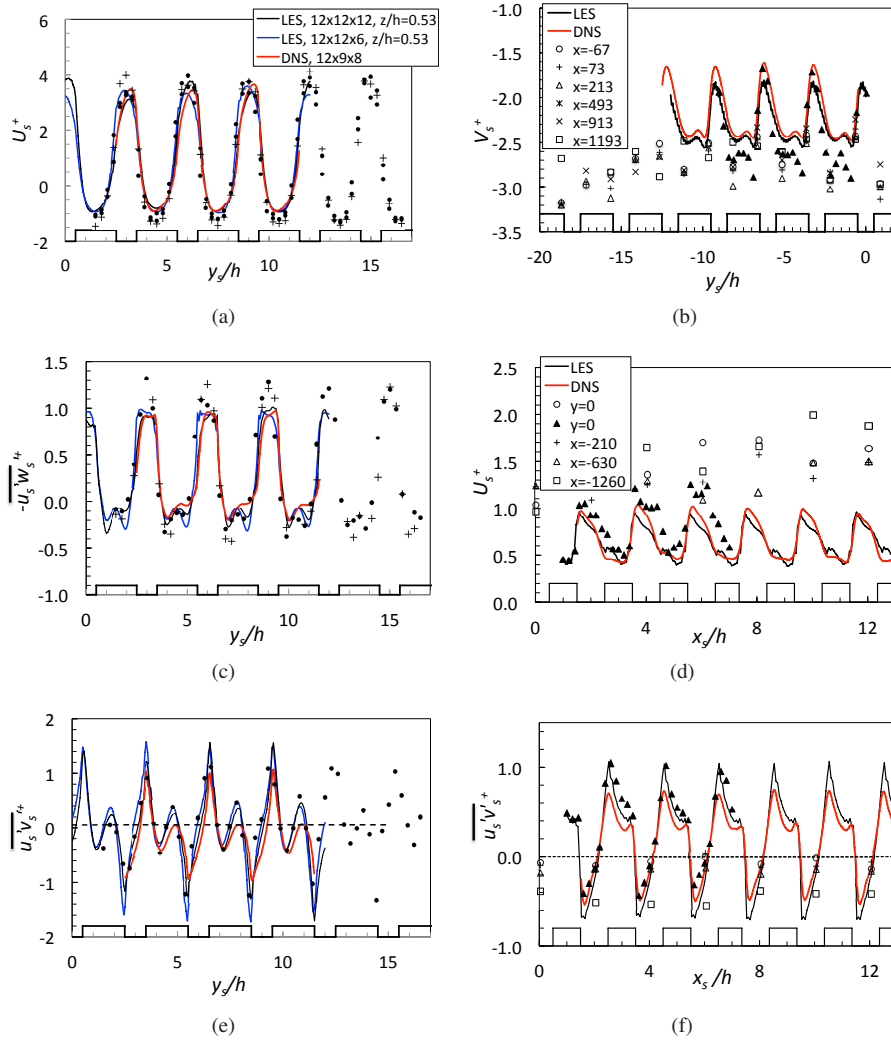


Fig. 10 Normalized velocity and stress profiles at $z/h = 0.53$ along streets for $\theta = 0^\circ$ (a,c,e) and $\theta = 45^\circ$ (b,d,f). Street coordinates are used throughout and the location of the array blocks is indicated at the bottom of each figure. In (a,c,e) the laboratory y -locations have, for convenience in comparison, been shifted by $9h$ and in all plots the origin of coordinates in the numerical data files has been shifted to cover the lab range conveniently. Symbols refer to laboratory data. Filled black triangles (in b,d,f) are from more closely resolved traverses. The legend for (c,e) is that for (a) and the legend for (f) is that for (b).

516 computed profiles. This is illustrated in Fig.11, which shows DNS lateral profiles
 517 of U^+ along the y streets at three mesh node points nearest $z/h = 1$, compared with
 518 laboratory data taken nominally at $z/h = 1$. It is clear that except near the peaks, most
 519 of the laboratory data points lie between the lateral DNS profiles at $z/h = 0.984$ and
 520 1.016 , as expected. Although the mesh was coarser, LES results (not shown) are quite

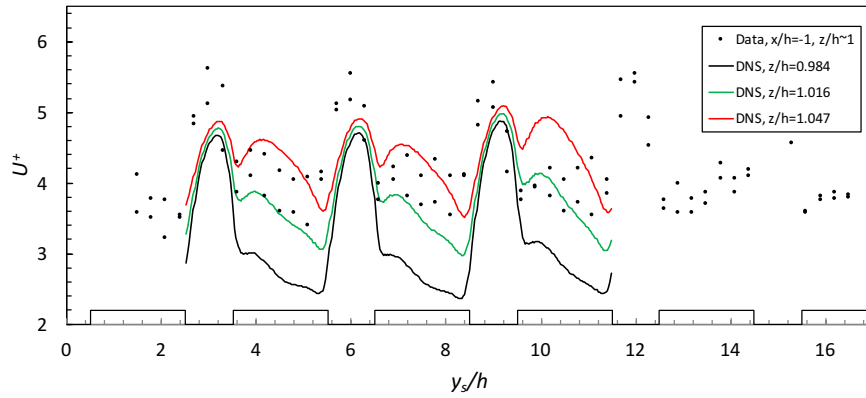


Fig. 11 Lateral U^+ profiles at $\theta = 0^\circ$ along the y streets, near $z/h = 1$. Block locations are indicated at the bottom of the figure.

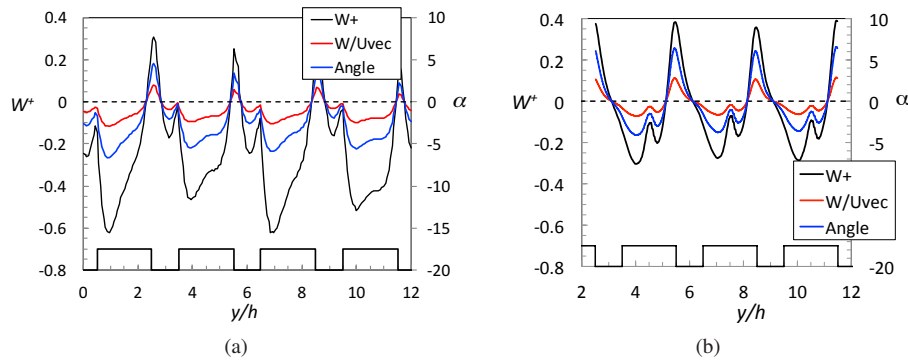


Fig. 12 Mean vertical velocity along the long (y) street centreline at $z/h = 1.03$ for the $\theta = 0^\circ$ case. The left-hand axes refer to both W^+ and W/U_{vec} whereas the right-hand axes refer to the flow angle, α , in the vertical plane. Block locations are shown at the bottom of the figures. (a) LES; (b) DNS.

521 similar. It is worth noting that the DNS profiles show small differences in successive
 522 sections of the array – for the $z/h = 1.047$ profile, for example, the peak U^+ around
 523 $y/h = 9$ is larger than at the equivalent locations around $y/h = 6$ and 3 . This may
 524 suggest either incomplete statistical convergence or, more likely, it is the effect of
 525 essentially stationary longitudinal rollers above the array indicated by the non-zero
 526 dispersive stresses there, discussed in Sect.3.2.

527 **5 Further results and discussion**

528 Dispersion of pollutants within the canopy region depends partly on the extent to
 529 which the flow can transport material into or out of the canopy. Despite the impor-
 530 tant influences of turbulence, this will clearly depend somewhat on the nature of the
 531 mean vertical flow at the canopy top. Figure 12 shows the variation of mean verti-

cal normalized velocity (W^+) along the centreline of the y -streets (i.e. parallel to the long faces of the obstacles) for the $\theta = 0^\circ$ case. Data were ensemble averaged across all available street centrelines in the domain and for the LES (Fig.12a) are at the first mesh point height above $z/h = 1$ ($z/h = 1.03$) whereas, for the DNS (Fig.12b), they are interpolated to the same height (from the data corresponding to the U^+ data shown in Fig.11). Data at the lower LES mesh point ($z/h = 0.97$) are similar to those shown in Fig.12a. The figure includes variations of the ratio W/U_{vec} , where U_{vec} is the magnitude of the velocity in the horizontal plane, and the angle to the horizontal of the total mean flow vector. It is evident that there are regions of both inflow and outflow – i.e. negative and positive W (as there must be when spatially averaged, but not necessarily in individual profiles such as those at a specific x). The strength of the mean flow is not particularly large, as seen by the variations of the flow angle (in the vertical plane), which do not exceed about 5° at most. Similarly, although the DNS W^+ values differ noticeably from the LES (cf. Figs.12a and 12b), they are small compared with the horizontal component – the W/U_{vec} ratio is below 0.1 everywhere.

Perhaps the most interesting feature of Fig.12 is that over each repeating unit (e.g. from $y/h = 3$ to $y/h = 6$) there is significant asymmetry in W^+ about the centre ($y/h = 4.5$), independent of whether LES or DNS results are considered. This is also evident in Fig.11. If the approach flow were at 90° to the block face and the lateral side force on the canopy were zero, W should be symmetric about that point. One must conclude that one or both of those requirements are not precisely satisfied or, alternatively, that small numerical inaccuracies are sufficient to produce this asymmetry. Unexpected asymmetry evidenced by non-zero lateral (V) velocities was discussed in Sect.4 (in relation to Fig.8b) and it is perhaps not surprising that this small asymmetry is most clearly seen within the separated shear layer around $z/h = 1$ in quantities that have large gradients there and are anyway very small. The computed flow angle at the top of the domain was only about 0.1° for this case and the lateral array force (normal to the flow direction at the top of the domain and the sum of pressure and viscous contributions) was also practically zero, as expected. Note that the lateral force normal to the forcing direction must inevitably be zero in a numerical computation, as explained by Claus et al. (2012). We therefore conclude that small numerical inaccuracies are sufficient to produce the asymmetry in W and, indeed, yield noticeable differences between the LES and DNS data in Fig.12 (there were, likewise, differences between DNS and LES in the unexpected non-zero V values within the canopy - Fig.8b). These differences might also be a result of small differences in dispersive stresses just above the canopy. This all emphasises the point that numerical computations of these kinds of flow are not as straightforward as one might at first imagine – a salutary warning to computationalists!

Contour plots of W^+ at $z/h = 1.0$ are shown in Fig.13a for all array orientations. In every case, there are significant areas of outflow, as must inevitably be the case since the spatially-averaged mean value must be zero (at all heights, in fact, by mass continuity). The regions of outflow, however, are different: for $\theta = 0^\circ$ they are concentrated at the trailing edge of the obstacle roofs and downstream of the side edges whereas, for $\theta = 90^\circ$, they lie along the side edges and front face. Since one might intuitively have expected the obstacles to generate delta-wing type vortex motions in the $\theta = 45^\circ$ case, it is interesting that there is, nonetheless, a region of outflow

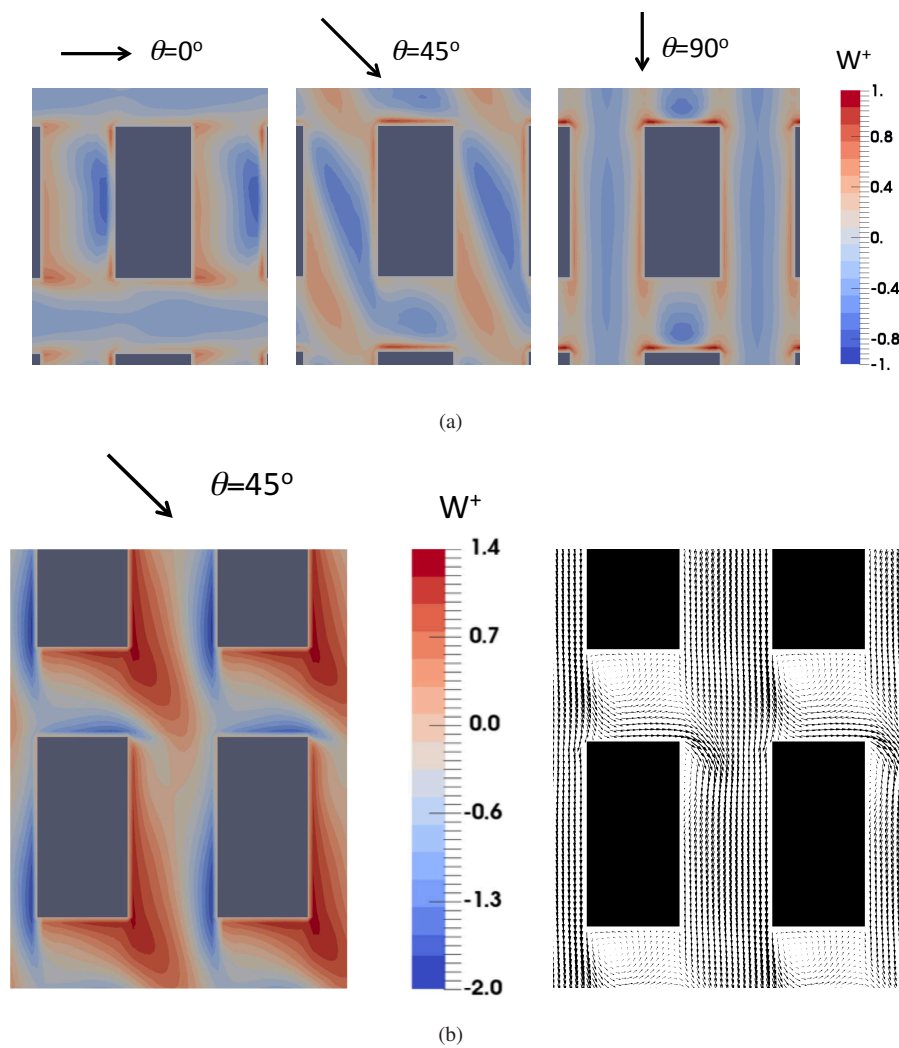


Fig. 13 (a) Contour plots of the normalized mean vertical velocity, W^+ , at $z/h = 1$, from the LES data at all three array orientations. (b) For $\theta = 45^\circ$ and $z/h = 0.5$, contour plots of W^+ (left) and flow vectors (right) in the horizontal plane.

578 downstream of the rearmost corner. If the influence of turbulent fluxes at $z/h = 1$
 579 was negligible, these plots would indicate the regions where any pollutants emitted
 580 within the canopy would be expected to be transported out to the boundary layer
 581 above. Likewise, some would be transported back into the canopy from aloft in the
 582 regions of negative W^+ . However, it is likely that the effects of turbulent transport are
 583 equally if not more important; the issue will be explored in the subsequent dispersion
 584 paper, but it is worth noting here that Belcher et al. (2015) (for an array of cubical ob-

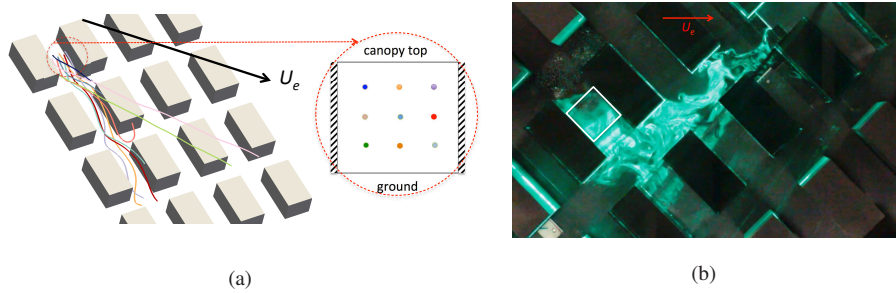


Fig. 14 (a) Tracers following the meanflow (i.e. mean flow pathlines) for the $\theta = 45^\circ$ case. The arrow shows the wind direction aloft. The right-hand sketch shows the origins of the nine coloured traces - equispaced in the street cross-section. The LES data were used. (b) Snapshot from video taken for $\theta = 45^\circ$. The ground-based square smoke source (70×70 mm), outlined by the white square, is located at the centre of a long street and the (green) laser sheet showing the smoke is coincident with the horizontal plane at $z/h = 0.64$ and is viewed from above.

585 stacles) suggest that, indeed, turbulent transport is dominant compared to advection
 586 with mean W , but this is probably not true near the upwind edge of the array or if the
 587 obstacle height varies significantly.

588 A similar contour plot is shown in Fig.13b for $\theta = 45^\circ$, but at the canopy half-
 589 height, $z/h = 0.5$. It is evident (see the left-hand plot) that the upward flows (positive
 590 W^+) are considerably stronger and more extensive than those at the top of the canopy,
 591 seen in Fig.13a (centre plot). To compensate, the downward flows, although restricted
 592 to thinner regions near the edges of the blocks, have significantly greater magnitude.
 593 The horizontal component of the total mean flow is shown in the vector plot (at the
 594 right-hand side of Fig.13b). The recirculating region behind the rearward short faces
 595 of the blocks can be seen, but the dominant feature is that the flow in the long streets
 596 (parallel to the longer side faces) is predominantly in the along-street (y_s) direction,
 597 despite the 45° wind direction aloft. This feature of canopy flows for wind directions
 598 not normal to obstacle faces was discussed by Claus et al. (2012) and is likely to
 599 remain a strong feature of urban canopies independently of the precise array geome-
 600 tries, unless the obstacle sizes and orientations are different from one another so the
 601 array does not embody any long continuous streets. A similar ‘street steering’ effect
 602 has also been observed in the field (e.g. Balogun et al., 2010; Carpentieri and Robins,
 603 2010). Figure 13b suggests that the $2h$ streets of the present array are just long enough
 604 to be representative for the street network modelling approach.

605 As an example of possible pollutant pathways in the absence of any turbulence
 606 effects Fig.14a shows (from LES data) mean flow pathlines originating from a grid
 607 of nine points in the vertical plane at the centre of the long (y_s) street and equally
 608 spaced between themselves and the obstacle side walls. There is a helical flow within
 609 the street but from some points the ‘tracers’ can escape above the canopy (via the
 610 positive vertical mean flow regions discussed above) and then they rapidly align with
 611 the mean flow aloft. Side views of the same results show that in no case do the tracers
 612 reach heights above $z/h \approx 1.1$.

613 It is worth noting that data like those presented in Figs.13 and 14a would be
614 almost impossible to obtain from laboratory or field experiments. (An indication
615 of what can be achieved, however, is seen in Carpentieri et al., 2009). The fig-
616 ures are therefore examples of the added value provided by numerical computa-
617 tions and are clearly helpful in providing further understanding of the canopy flows.
618 They should be interpreted with care, however. As indicated earlier, the presence
619 of large-amplitude turbulent motions will ensure that tracers would not actually fol-
620 low the mean flow particle paths shown in Fig.14a. We illustrate this by showing in
621 Fig.14b, for comparison with Fig.14a, a corresponding but instantaneous snapshot of
622 the smoke pattern arising in a laboratory experiment on a plane not far from the mid-
623 height of the canopy. The source of smoke laden air was an area of size $h \times h$ at $z = 0$
624 and located at the centre of a long (y_s -direction) street. It is clear that (i) some smoke
625 can move ‘upstream’ of the source location and (ii) some can arrive at considerable
626 distances laterally within the canopy - much further than would be suggested by the
627 selected mean flow tracers of Fig.14a. The consequences of this rapid lateral spread
628 are sometimes seen in dispersion measurements in the field – for example, the mea-
629 surements in central London described by Wood et al. (2009). Views of a horizontal
630 plane at $z/h = 2$ (not shown) indicate (iii) that the smoke can reach heights well in
631 excess of the $z/h = 1.1$ suggested by mean flow tracers and certainly above $z/h = 2$.
632 These three facts alone are sufficient to demonstrate that the turbulence fluxes are
633 very significant, so that mean flow tracers like those shown in Fig.14a should indeed
634 be interpreted with caution. It is crucial to study these fluxes in detail and this will be
635 a topic for the subsequent dispersion paper describing the concentration fields within
636 and above the canopy.

637 Not only are the turbulent fluxes important but it should be noted that, within the
638 canopy, dispersive fluxes – arising from the spatial variability of the local time-mean
639 velocities in horizontal planes – are also large. This is illustrated in Fig.15, using
640 the LES data. The data have been normalized in each case by the corresponding
641 Reynolds stress at the appropriate height and it is clear that they can be of the same
642 order as the latter over large parts of the canopy height, as found in previous studies
643 (e.g. Coceal et al., 2006). This emphasises the high degree of spatial variability of
644 flow properties within the canopy. Although in some circumstances pollutants may
645 be well mixed (so that concentrations are not too non-uniform) this does not imply
646 uniformity in the flow variables. Since the flows are strongly three-dimensional and
647 inhomogeneous within the canopy, the usual decomposition of stresses in coordinates
648 aligned with (e.g.) the forcing direction is perhaps not particularly useful; one could
649 argue that principle stress coordinates should be used. However, this seems an unnec-
650 essary complication in the present context and would not add very much to physical
651 understanding.

652 **6 Final discussion and conclusions**

653 We remark first on conclusions arising from the wind-tunnel experiments. Measure-
654 ments in an extensive array of this kind are particularly challenging, not least because
655 of the need to maintain positional accuracy relative to the array blocks whilst moving

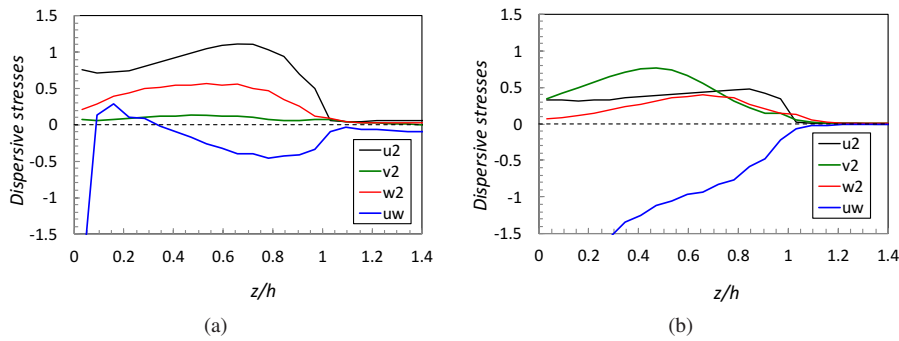


Fig. 15 Vertical profiles of dispersive stresses within the canopy from the LES for $\theta = 0^\circ$ (a) and $\theta = 45^\circ$ (b). Each dispersive stress, at each height, is normalized by the corresponding (time- and domain-averaged) Reynolds stress at that height.

656 across several modules. The consequences are most obvious when traversing across
 657 the shear layers in the flow separating from the building block roof and walls, as is
 658 made very clear from inspection of the DNS results in Fig.11. Related issues arise
 659 from the sensitivity of the flow to slight errors in alignment in the 0° and 90° cases.
 660 Although considerable efforts were made to improve experimental techniques, these
 661 matters remained the main cause of uncertainty in the data. The weak mean cross-
 662 flow seen in the computations for the 0° case implies a consistent, though weak drift
 663 in the centre line of a plume dispersing through the array. Drift of this nature is likely
 664 to be of greater magnitude in the wind-tunnel work, due to overall alignment error,
 665 though variable to some degree, reflecting local errors in block alignment. These
 666 matters will be returned to in comparing measured and predicted dispersion in the
 667 subsequent paper.

668 Next, conclusions arising from the numerical computations are given. Firstly, it
 669 has been shown that the computed flows within the present urban-type canopy are not
 670 very sensitive to the domain height. This is significant, as it makes it computationally
 671 more efficient to model pollutant releases within the canopy. Nonetheless, we recom-
 672 mend a domain height of at least six canopy heights in order to capture the most
 673 important turbulent features just above the canopy, some of which are necessarily
 674 linked to the turbulent flow at greater heights.

675 In common with previous work, some of our results suggest the possible pres-
 676 ence of longitudinal, slowly-evolving rolls above the canopy. These can be strongly
 677 attenuated, if not completely damped out, if the computational domain is too small.
 678 For the present canopy morphology, a domain plan area of $6h \times 6h$ seems too small
 679 (see Sect.4), especially for flow directions normal to the obstacle faces; these direc-
 680 tions are in one sense pathological and allow the computed flow to break symmetry
 681 and contain a mean spanwise flow that is increasingly enhanced as the domain size
 682 decreases. The presence of slowly-moving rolls aloft also has implications for mod-
 683 elling limited-duration pollutant releases, because downstream concentration patterns
 684 could depend somewhat on the location of the rolls (with respect to that of the source)
 685 over the particular release and dispersion times. At this stage it is not clear how sensi-

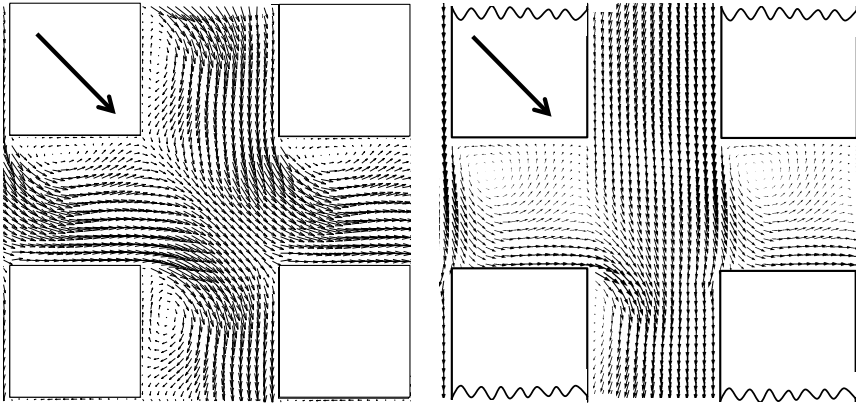


Fig. 16 Mid-height ($z/h = 0.5$) flow vectors for $\theta = 45^\circ$. (a) Square cube array - from Claus et al. (2012). (b) the present array; note that only half of each $h \times 2h \times h$ obstacle is shown, so that only downwind half of the obstacles is shown at the top of the figure and the upstream half at the bottom.

686 tive this feature is to the specific array morphology, but it is certainly something that
 687 should be considered in designing numerical experiments on such flows.

688 Secondly, as noted above, the present results illustrate the difficulty in achieving
 689 perfect flow symmetry for cases where the geometry would lead one to expect it. This
 690 is true both for laboratory and numerical modelling. It may be a result of the specific
 691 canopy morphology having its lowest drag condition at some small angle to that for
 692 which symmetry is expected, but further work would be needed to confirm this and, if
 693 this *is* the cause, the behaviour would certainly vary with canopy morphology. What-
 694 ever the cause, this asymmetric feature is a further indication of the care needed in
 695 designing and executing such experiments. In nearly all the extant literature, insuf-
 696 ficient data are shown to give confidence that such a spanwise (symmetry-breaking)
 697 flow is *not* present, so the present results provide a further cautionary lesson.

698 Thirdly, the present canopy has obstacles sufficiently long compared with their
 699 heights to yield extensive flow channelling along streets. This is most clearly illus-
 700 trated by Fig.16. The region in which the flow turns to become parallel to the long
 701 sides of the obstacles is no more $1h$ in extent (in both x_s and y_s directions) – a lit-
 702 tle smaller than what was found in the more classical (square) cube array studies of
 703 Claus et al. (2012), shown on the left of the figure. Across the whole of the down-
 704 wind half of the long street the flow for the present canopy is closely aligned with
 705 the obstacle faces, despite the 45° flow orientation aloft. This supports the sugges-
 706 tion made in Sect.5 that the streets are long enough to be representative for street network
 707 modelling approaches; shorter streets would probably not be sufficient and it will be
 708 interesting to see how well network models can predict concentrations in the present
 709 canopy. That will be the subject of a forthcoming paper.

710 Finally, it is worth noting that the domain-averaged axial mean velocity profiles
711 through the canopy cannot be sensibly fitted by an exponential profile, for any of
712 the wind directions considered. MacDonald (2000) was perhaps the first to make
713 the suggestion that profiles could be so fitted (although such profiles in vegetation
714 canopies had long been proposed Cionco (1965)) and recently Yang et al. (2016)
715 have suggested that good fits to exponentials *can* be obtained for a wide range of
716 arrays comprising cubical obstacles. However, although they studied arrays of cubes
717 with $\lambda_p = 0.25$, identical to those studied by Coceal et al. (2006), Leonardi and Cas-
718 tro (2010) and Claus et al. (2012), the canopy velocity profiles they obtained differed
719 significantly from those obtained by all these latter authors. It seems likely that their
720 mesh was not fine enough (having only eight points across the height of the canopy)
721 to resolve the thin shear layer at the canopy top. A 25% area coverage is almost within
722 the full ‘skimming’ regime (‘d-type’ roughness, in the classical roughness terminol-
723 ogy) and it may well be that for much lower λ_p typical of ‘k-type’ roughness when
724 sheltering between obstacles is less prevalent, the velocity profiles can be reasonably
725 modelled by exponentials. This remains an open question which will be considered
726 in a further paper, but there is no doubt that the present computations can be used to
727 show that assumptions typically made to derive an analytical (exponential) velocity
728 profile model are generally far from valid in urban type canopies.

729 Despite the various uncertainties discussed in both the laboratory and the compu-
730 tational studies, an important general conclusion of the work is that the computations,
731 whether by LES or DNS, satisfactorily capture the salient details of the complex,
732 three-dimensional flow within the canopy, in that the results agree as well as can be
733 expected with the wind-tunnel data. This is very encouraging, for it suggests that any
734 subsequent differences found between computed and laboratory statistics of disper-
735 sion behaviour, for the same configurations and using the same methods, will *not* be
736 a result of inadequate flow computations.

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