

# *Analysis of pollutant entrainment From localised sources in a street network*

Article

Accepted Version

Cezana, F. C., Goulart, E. V., Reis Jr, N. C. and Coceal, O.  
ORCID: <https://orcid.org/0000-0003-0705-6755> (2021)  
Analysis of pollutant entrainment From localised sources in a  
street network. *Boundary-Layer Meteorology*, 179. pp. 241-  
258. ISSN 0006-8314 doi: <https://doi.org/10.1007/s10546-020-00598-7> Available at <https://centaur.reading.ac.uk/94902/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1007/s10546-020-00598-7>

Publisher: Springer

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

[www.reading.ac.uk/centaur](http://www.reading.ac.uk/centaur)

**CentAUR**

Central Archive at the University of Reading

Reading's research outputs online



1 **Analysis of Pollutant Entrainment From Localised**  
2 **Sources in a Street Network**

3 **FC Cezana · EV Goulart · NC Reis Jr ·**  
4 **O Coceal**

5  
6 Received: DD Month YEAR / Accepted: DD Month YEAR

7 **Abstract** The propagation of a pollutant emitted from localised sources both  
8 within and above a regular street network is studied by analysing data from  
9 direct numerical simulations of passive scalar dispersion. Two wind directions  
10 are considered, corresponding to aligned and oblique flow with respect to the  
11 street axes. Particular attention is paid to the role of entrainment of the scalar  
12 into the urban canopy from an elevated source and re-entrainment of material  
13 originally released further upstream from a ground source. The variation of  
14 concentration differences and vertical fluxes between the streets and the air  
15 above as a function of distance reveals important differences between the rate  
16 of lateral and vertical mixing for the two sources. Detrainment and entrainment  
17 need a longer fetch to equilibrate for the elevated source than for the ground  
18 source. There are large differences between the advection and detrainment  
19 velocities for the aligned and oblique cases, so that a change in wind direction  
20 could affect ventilation efficiency considerably. Time scales associated with  
21 different dispersion processes are computed and the time of first appearance of

---

FC Cezana  
Federal University of Espirito Santo, Vitoria, Brazil

EV Goulart  
Federal University of Espirito Santo, Vitoria, Brazil  
Tel.: +55-27-40092177  
Fax: +55-27-40092148  
E-mail: elisa.goulart@ufes.br

NC Reis Jr  
Federal University of Espirito Santo, Vitoria, Brazil

O Coceal  
National Centre for Atmospheric Science (NCAS), Department of Meteorology, University  
of Reading, PO Box 243, Reading, RG6 6BB, UK

the scalar from the onset of release in different streets is mapped. It is shown that re-entrainment can provide a shortcut dispersion pathway for reaching certain parts of the network. This is particularly striking in the case of oblique flow, when material can be transferred by entrainment up to twice as fast as it could by advection. Taken together, these results highlight the overall message that vertical exchange is a two-way process and that entrainment needs to be considered in the context of emergency-response as well as urban ventilation.

**Keywords** Air pollution · Direct numerical simulation · Pollutant entrainment · Street network · Urban dispersion

## 1 Introduction

Cities are the world's major economic, social and geographical centres, concentrating most of the global investments and resources. Consequently, the number of people living in urban spaces is growing. However, demographic growth has been accompanied by several problems, among them atmospheric pollution. Thus, it is expected that human exposure to hazardous substances is higher, especially in areas where the density of population and traffic are relatively high. The urban morphology can either dilute or increase the concentration of pollutants at pedestrian level, depending on complex local dispersion processes and building geometry. Therefore, understanding the transport and dispersion of pollutants in populated areas is an important aspect of air quality management and mitigation strategies. Due to the complexity of the urban environment and the interplay of different flow processes several aspects of urban dispersion remain little-understood (Britter and Hanna 2003; Soulhac et al. 2009; Belcher et al. 2012). One such process is entrainment of pollutants into the urban canopy, either from outside sources or from material originally released within the canopy further upstream (re-entrainment). This process is an important determinant of the general issue of urban ventilation or urban breathability (Neophytou and Britter 2005), which is gaining greater recognition as a critical aspect of urban sustainability (Peng et al. (2020)).

The concept of *breathability* has been linked to that of the *vertical exchange velocity* (Neophytou and Britter 2005). This link has been invoked in numerous subsequent studies (e.g. Panagiotou et al. (2013); Chen et al. (2017); Shen et al. (2017)). For instance, Chen et al. (2017) investigated how the building height influences city breathability using wind tunnel experiments and computational fluid dynamics (standard  $k - \epsilon$ ) modelling in a medium-density and a compact-density model. The authors investigated the in-canopy horizontal velocity and the exchange velocity at the top of the canopy which they related to city breathability. They found that for medium-density models the building height variations increase the exchange velocity of taller buildings, but reduces that of lower buildings. The compact-density urban model had weaker in-canopy horizontal velocity and vertical turbulent exchange velocity than the medium-density model. Shen et al. (2017) conducted a study of dispersion

65 of a passive scalar in the turbulent flow over arrays of cubes under neutral and  
66 stable stratification using a large-eddy simulation. The study was designed to  
67 investigate the effect of the plan area density on the flow and dispersion. They  
68 found that in general, as the plan area density increases the in-canopy concen-  
69 tration is higher. For a skimming flow, the authors showed that for a stable case  
70 the vertical transportation of scalar is weaker and therefore the concentration  
71 is higher within the canopy compared to the neutral case. For neutral condi-  
72 tions, the advection scalar flux within the canopy reduces with distance from  
73 the source as the plan area density increases. The authors suggested that this  
74 reduction is due to the enhancement of the vertical scalar transfer. For stable  
75 conditions, advection scalar flux within the canopy has a slower decrease with  
76 distance from the source because the scalar transfer at canopy top is relatively  
77 weaker. Chen et al. (2017) and Shen et al. (2017) are merely two examples of  
78 many recent studies that highlight the importance of characterising vertical  
79 exchange for understanding urban ventilation. However, vertical exchange is a  
80 two-way process; while there is an abundance of experimental and numerical  
81 work on detrainment of pollutants out of the urban canopy top, there has been  
82 very little work on entrainment into the canopy.

83 Basic understanding of entrainment is needed for several reasons, both  
84 practical and fundamental. First, it is relevant for source attribution assess-  
85 ments and emission reduction measures. For example, if significant amounts  
86 of pollutants released elsewhere are entrained in already polluted areas, then  
87 the effectiveness of clean air zones for controlling local emissions may need  
88 to be re-examined. Secondly, accidental releases from industrial areas may  
89 spread toxic fumes and particulates over neighbouring residential areas or city  
90 centres via entrainment. Such was the case, for instance, during a major fire  
91 incident at the Buncefiled oil depot north of London, UK, during December  
92 2005. Enormous quantities of PM10 were released, equivalent to 6 per cent of  
93 the annual UK emission, which led to the closure of hundreds of schools and  
94 public places and home evacuations over two days (Targa et al. 2006). Thirdly,  
95 even under normal conditions the air above an urban area will have a different  
96 concentration of pollutants and possibly different chemical composition from  
97 that within streets. For example larger ozone concentrations may be advected  
98 from rural surroundings. Hence, entrainment may alter the types and rates of  
99 chemical reactions in streets (Harrison 2018). Fourthly, dispersion models need  
100 to include the effect of entrainment, e.g. Belcher et al. (2015), Goulart et al.  
101 (2018) and Hertwig et al. (2018) showed that it becomes important within  
102 a few streets downstream of a release and that the performance of a street  
103 network dispersion model is substantially improved by taking it into account.

104 Aside from the insights gained from the modelling studies of Belcher et al.  
105 (2015), Goulart et al. (2018) and Hertwig et al. (2018), there is little in the  
106 published literature focusing on entrainment and re-entrainment in urban  
107 canopies. Garbero et al. (2010) performed a series of wind-tunnel experiments  
108 to study different transfer processes in a street network, including channelling  
109 along streets, mixing in intersections and vertical exchange between the streets  
110 and the overlying flow. However, they did not consider entrainment explicitly.

111 Belcher et al. (2012) refers to unpublished material (DAPPLE 2011) which  
112 showed some evidence of the effect of entrainment and re-entrainment from  
113 elevated and ground sources respectively based on wind-tunnel measurements  
114 pertaining to a site in central London. The results showed that entrainment  
115 caused a widening of the initially narrow plume from a localised elevated source  
116 once the material entered the street network, where the plume angle spanned  
117  $90^\circ$  a sector. For a street level emission, the plume initially dispersed within  
118 a  $90^\circ$  sector as a result of the local building geometry and was thereafter  
119 confined to a slightly narrower sector. Carpentieri et al. (2012) and Carpen-  
120 tieri et al. (2018) performed detailed wind-tunnel measurements of pollutant  
121 fluxes and quantified the mean and turbulent components of horizontal and  
122 vertical fluxes. Hertwig et al. (2018) related these wind-tunnel results to the  
123 role of entrainment. Given the paucity of experimental data on entrainment  
124 the use of simulated data should be considered. Direct numerical simulation  
125 (DNS) and large-eddy simulation (LES) are well-established tools for perform-  
126 ing fundamental studies of flow and dispersion (Belcher et al. 2012). Indeed  
127 the use of such data is sometimes preferable to the direct use of experimental  
128 measurements, provided they are validated first. Advantages of such simu-  
129 lations include: they can be performed under controlled conditions, can be  
130 designed to focus on particular processes and produce data at much higher  
131 spatial resolution than is typically possible experimentally. In particular, DNS  
132 is different from other modelling in that it is a direct solution of the Navier-  
133 Stokes equations without any modelling assumptions (Moin and Mahesh 1998;  
134 Pope 2000). The only errors in DNS are due to finite discretization and hence  
135 error margins in DNS are typically lower than experimental ones. DNS simu-  
136 lations over urban-like geometry have yielded results in excellent agreement  
137 with carefully-conducted wind-tunnel experiments (Coceal et al. 2006, 2007).

138 In relation to the under-explored subject of entrainment, key basic ques-  
139 tions that need to be addressed include: (i) How much material is entrained,  
140 and how quickly? (ii) When and where is entrainment most important? (iii)  
141 What controls it in an urban canopy? This paper presents a preliminary study  
142 of these questions by analysing data from direct numerical simulations (DNS)  
143 of passive scalar dispersion over an idealised street network. The data used  
144 and the simulations that generated them are presented in section 2. In view  
145 of the focus on entrainment and re-entrainment, the dispersion characteristics  
146 from an elevated source are compared against those from a ground source (sec-  
147 tion 3). The development in space and in time of the concentration through  
148 the network is characterised and interpreted in terms of underlying dispersion  
149 mechanisms and time scales linked with different processes (section 4). We  
150 summarise the main findings and highlight their novelty in section 5.

## 151 **2 Numerical Modelling and Data**

152 The data used in this study is based on direct numerical simulation (DNS)  
153 of turbulent flow over arrays of cubes, which represent an idealised urban

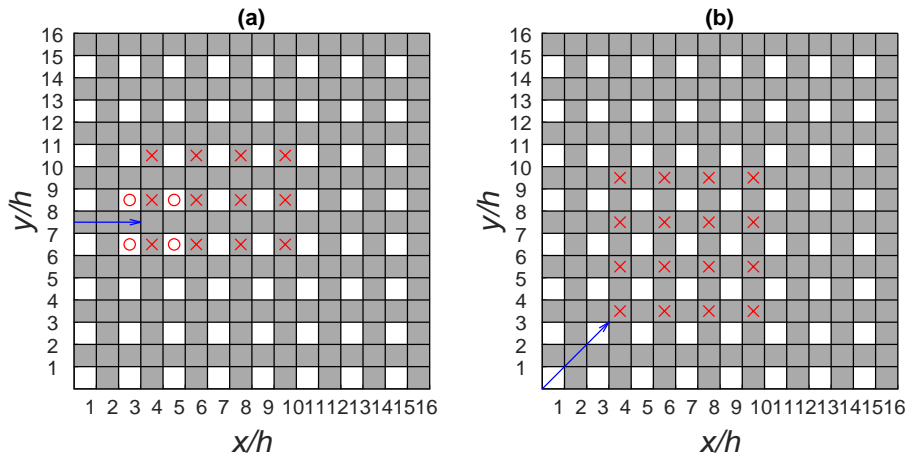
154 area. The numerical methods are described in Coceal et al. (2006) and Co-  
155 ceal et al. (2007). In brief, the Navier-Stokes equation was discretized using  
156 a second-order central finite difference scheme in space and a second-order  
157 Adams Bashforth scheme in time, based on the pressure correction method.  
158 The Poisson equation for pressure was solved using a multigrid method. The  
159 code was parallelized using Message Passive Interface (MPI).

160 The DNS runs that generated the datasets analysed here are described in  
161 Branford et al. (2011), and they additionally solved the passive scalar equation  
162 coupled to the computed velocity field, with an ensemble of localised sources  
163 as described below. Detailed descriptions of the numerical methods, tests and  
164 validation of flow statistics against wind-tunnel data are given in Coceal et al.  
165 (2006) and Coceal et al. (2007) and corresponding details and validation of  
166 concentration statistics against water-channel data are reported in Branford  
167 et al. (2011). Essential details of the simulations are summarised in the fol-  
168 lowing.

169 A plan view of the domain setup is shown in Figure 1 and involves a  
170 regular array of cubical obstacles of height  $h$ . The domain size was  $16h \times 16h$   
171 in the horizontal and  $8h$  in the vertical. In the present work we analyse data  
172 from two runs in which the wind direction is at  $0^\circ$  and  $45^\circ$  to the cube array.  
173 The simulations were conducted under conditions of neutral stability and fully  
174 rough turbulent flow. The Reynolds number based on the velocity magnitude  
175 at the top of the domain and the cube height was typically between 4750  
176 and 7000. The flow was maintained by a height-independent pressure gradient  
177 of magnitude  $u_\tau^2/H$ , where  $u_\tau$  is the total wall friction velocity and  $H$  is  
178 the domain height. The imposed boundary conditions were periodic in the  
179 horizontal directions, free-slip at the domain top and no-slip on the bottom  
180 and all cube surfaces.

181 A non-dimensional time scale characterizing the turnover time of eddies  
182 shed from the cubes can be defined as  $T = h/u_\tau$ . The simulations were run with  
183 a time step of  $0.00025T$ . Each run was spun up for a duration of approximately  
184  $200T$  to allow fully developed turbulence conditions. After this spin-up time,  
185 passive scalar was switched on and released at a steady rate  $q = 0.0574684$   
186 (mass per unit volume per unit time, in units chosen such that  $h = 1$ ,  $u_\tau = 1$   
187 and air density  $\rho = 1$ ) thereafter from an ensemble of sources located close  
188 to the ground (at  $z = 0.0625h$ ) within the array at  $z = 2h$  above the array;  
189 the source locations are indicated in Fig. 1. A sponge layer was applied at the  
190 boundary of the domain to prevent the scalar from re-entering the domain. At  
191 the top of the domain the scalar was allowed to escape.

192 For each run the sources were placed in equivalent locations so that they  
193 formed an ensemble of equivalent simultaneous releases. Statistics were then  
194 collected and averages computed over an interval of approximately  $100T$ . Aver-  
195 aging over an ensemble of releases helped in reducing the overall computational  
196 cost as it is equivalent to increasing the duration of the time series of one indi-  
197 vidual release for the same flow simulation. The ensemble-averaging was done  
198 by shifting the origin of the coordinate system for each source as follow: for  
199 the  $0^\circ$  run, such that the effective source location in each case is at  $(3.5h, 6.5h)$



**Fig. 1** Plan view of the computational domain in the DNS for a forcing direction of (a)  $0^\circ$  and (b)  $45^\circ$ . White squares denote building positions and grey areas denote the air space between them. Locations of ground sources at  $z = 0.0625h$  and elevated sources at  $z = 2h$  are denoted by red crosses and circles respectively. Blue arrows indicate forcing wind directions.

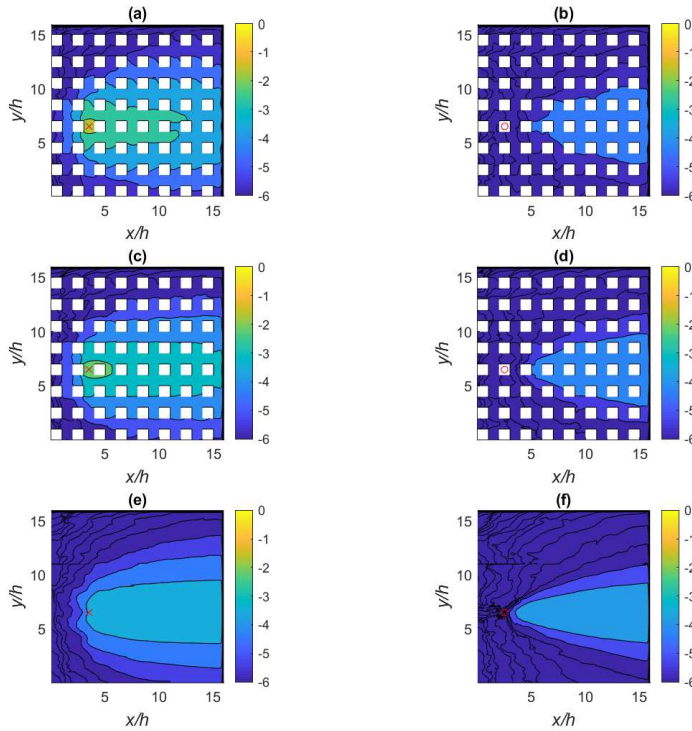
200 for the ground source and at  $(2.5h, 6.5h)$  for the elevated source; for the  $45^\circ$   
 201 run, the corresponding shifted location is at  $(3.5h, 3.5h)$ . The result of this  
 202 averaging is to produce concentration fields and time-series corresponding to  
 203 a single release at the given effective source location in each case.

204 For the  $0^\circ$  case, we shall refer to obstructed regions between buildings  
 205 as ‘canyons’ and to other unobstructed streets as ‘channels’, of which there  
 206 are two types: those between cubes and those between canyons. We expect  
 207 different flow patterns and hence different dispersion behaviours among these  
 208 three types of regions. For the  $45^\circ$  case there are only two types of regions:  
 209 ‘intersections’, which are directly linked to ‘streets’ on all four sides; the streets  
 210 themselves are between cubes on either side and are linked to intersections at  
 211 their ends. Hence, one might expect them to share characteristics of both the  
 212 canyons and channels of the  $0^\circ$  case.

### 213 3 Comparison Between Dispersion From an Elevated Source and a 214 Ground Source

215 A source located above a street network gives rise to characteristically differ-  
 216 ent dispersion patterns than a source within the network. In this Section we  
 217 describe these differences and explain them in terms of underlying dispersion  
 218 processes.





**Fig. 2** Contours of ensemble-averaged mean concentration at three different heights (a) and (b) at  $z = 0.5h$ , (c) and (d) at  $z = h$ , (e) and (f) at  $z = 1.5h$ , for the ground source (left panels) and elevated source (right panels) for the  $0^\circ$  run. The colour bars and concentration contours correspond to the common logarithm ( $\log_{10}$ ) of the concentrations. Locations of ground source at  $z = 0.0625h$  and elevated source at  $z = 2h$  are denoted by red crosses and circles respectively.

### 219 3.1 Mean Concentration Patterns

220 Fig. 2 shows contours of the ensemble-averaged mean concentration at three  
 221 different heights ( $z = 0.5h$ ,  $z = h$  and  $z = 1.5h$ ) for the ground source (left  
 222 panels) and the elevated source (right panels) for the  $0^\circ$  run. Not surprisingly,  
 223 there are several qualitative and quantitative differences in the dispersion pat-  
 224 terns from these two release locations. For the ground source by far the highest  
 225 concentration is found in the canyon where the source is located, indicating  
 226 trapping of the scalar in the wake of the building immediately behind it. This  
 227 persists up to the building height  $z = h$ , where the region of high concen-  
 228 tration is seen to extend into the wake of the next building downstream. A  
 229 nested series of roughly oblong-shaped contours enclose regions of comparable  
 230 concentration within the array. Above the array, at  $z = 1.5h$ , these regions  
 231 open up slightly downstream. In comparison, the corresponding concentration  
 232 pattern at the same height from the elevated source located at  $z = 2h$  is  
 233 more triangular and similar to a Gaussian plume shape. The difference can be

understood by thinking of the time-averaged pattern from the ground source as resulting from a much more diffuse effective source in the canopy underneath, once a dynamic equilibrium has been established (Goulart et al. 2018). As a consequence, the plume from the ground source differs markedly from a Gaussian shape both within and above the array, although it approximates a Gaussian far from the source (Coceal et al. 2014; Belcher et al. 2015).

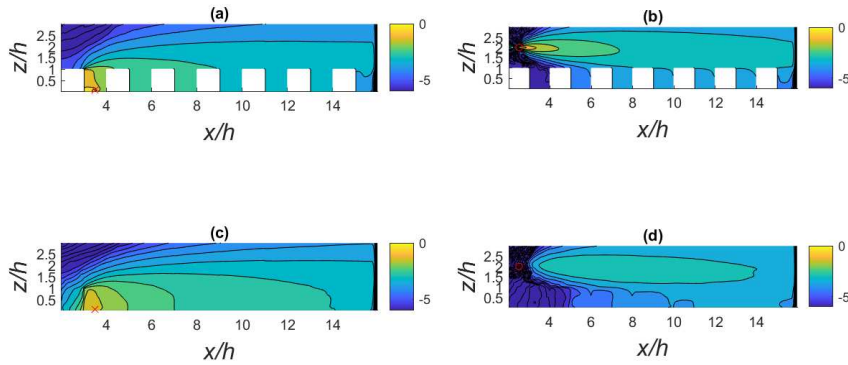
Fig. 2b and 2d show that entrainment from the elevated source into the urban canopy occurs fairly rapidly, within about two building heights downstream of the source. The resulting plume of entrained material retains a triangular shape within the array, and widens slightly. Comparison of Fig. 2b and Fig. 2f shows that the rate at which the plume widens once it is in the array is quicker than that of the material above. This is reminiscent of the wind-tunnel results from DAPPLE (2011) alluded to in the Introduction.

The entrainment of material into the canopy from the elevated source, and re-entrainment from the ground source can be seen more clearly in the contour plots in vertical planes shown in Fig. 3. For the ground source, initial rapid detrainment out of the canyon where the source is located is followed by re-entrainment over the next few canyons. Further on, the balance of these two processes results in a rapid approach to equilibrium, where the concentration within and above the array are eventually equalised. Similar results were reported by Goulart et al. (2018) and Hertwig et al. (2018). Fig. 3a and 3c show that this happens sooner over the row of buildings than over the open channels. The opposite appears to be the case for the elevated source. Here the approach to equilibrium happens quicker over the channels, and it is more gradual compared to the ground source. Despite the fairly rapid entrainment, the concentration within the canopy does not approach that above as quickly as for the ground source.

### 3.2 Concentration Differences Within and Above the Street Network

To analyse the approach to equilibrium more quantitatively, Fig. 4 plots the ensemble-averaged mean concentration at two heights  $z = 0.5h$  and  $z = 1.5h$  as a function of distance at lateral locations  $y = 6.5h$  and  $y = 7.5h$  for the ground source (Fig. 4a) and the elevated source (Fig. 4b). These locations were chosen to correspond to the unobstructed streets along which most of the scalar is channelled, due to their vicinity to the source location. Note that the concentration at  $z = 0.5h$  within the canyon in which the source is located (at  $x = 3.5h$ ) is off the scale of the plot, at  $\approx 0.058$ , nearly an order of magnitude larger than the value within the immediately adjacent channel at  $z = 0.5h$  (which is  $\approx 0.0064$ ) and more than two orders of magnitude larger than the concentration immediately above at  $z = 1.5h$ .

Fig. 4a shows that the lateral concentration differences in the array are generally small for the ground source, except for the canyon in which the source is located compared to the adjacent street in the channel, as noted above. There are somewhat larger lateral differences in the concentrations



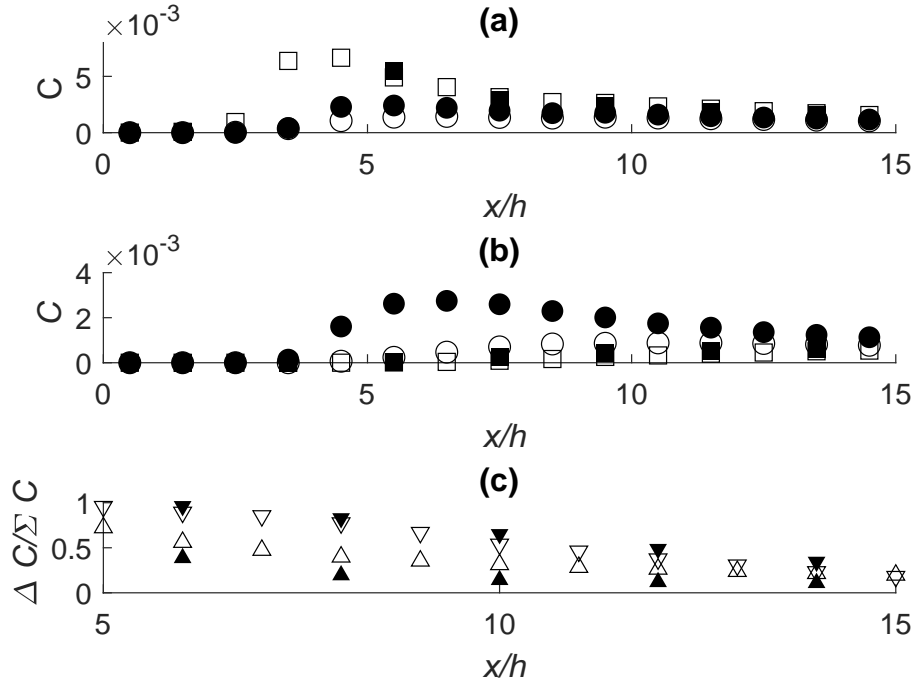
**Fig. 3** Contours of ensemble-averaged mean concentration in two vertical planes (a) and (b) at  $y = 6.5h$ , (c) and (d)  $y = 7.5h$  for the ground source (left panels) and elevated source (right panels) for the  $0^\circ$  run. The colour bars and concentration contours correspond to the common logarithm ( $\log_{10}$ ) of the concentrations. Locations of ground source at  $z = 0.0625h$  and elevated source at  $z = 2h$  are denoted by red crosses and circles respectively.

277 above the array, but these differences quickly decrease, and indeed all the  
 278 four concentration profiles nearly converge by the time the end of the array is  
 279 reached. For the elevated source, Fig. 4b shows that the lateral differences are  
 280 again relatively small within the array but are now considerably larger above,  
 281 due to the narrower plume from this source. Fig. 4c plots the absolute value of  
 282 the concentration difference between each street and above it as a fraction of  
 283 the sum of those concentrations for each source from the data shown in Fig.  
 284 4a and Fig. 4b. These plots reinforce the observations made in the previous  
 285 section on the relative rate of approach to equilibrium.

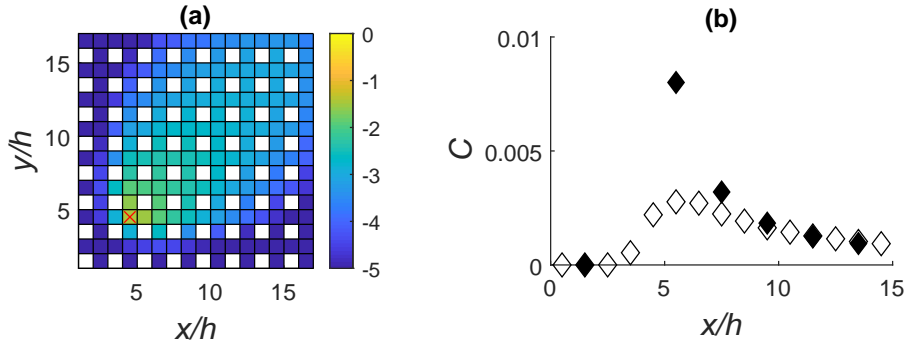
286 The effect of lateral dispersion is particularly important for oblique flow di-  
 287 rections, when it is enhanced by a topological mechanism, namely the diverging  
 288 of mean streamlines around buildings (Belcher et al. 2015). This is illustrated  
 289 in Fig. 5, which shows the ensemble-averaged and box-averaged mean concen-  
 290 tration in each street resulting from a ground source release at  $(3.5h, 3.5h)$ . The  
 291 enhanced lateral dispersion coupled with strong initial detrainment results in  
 292 a rapid decrease in the centreline concentration with distance from the source,  
 293 so that the concentrations within and above match after a distance of only  
 294 about  $4h$  downstream of the source. Note again that the concentration in the  
 295 street in which the source is located (at  $x = 3.5h$ ) is off the scale of the plot,  
 296 at  $\approx 0.0361$ .

### 297 3.3 Detrainment and Entrainment Scalar Fluxes Across the Roof Level

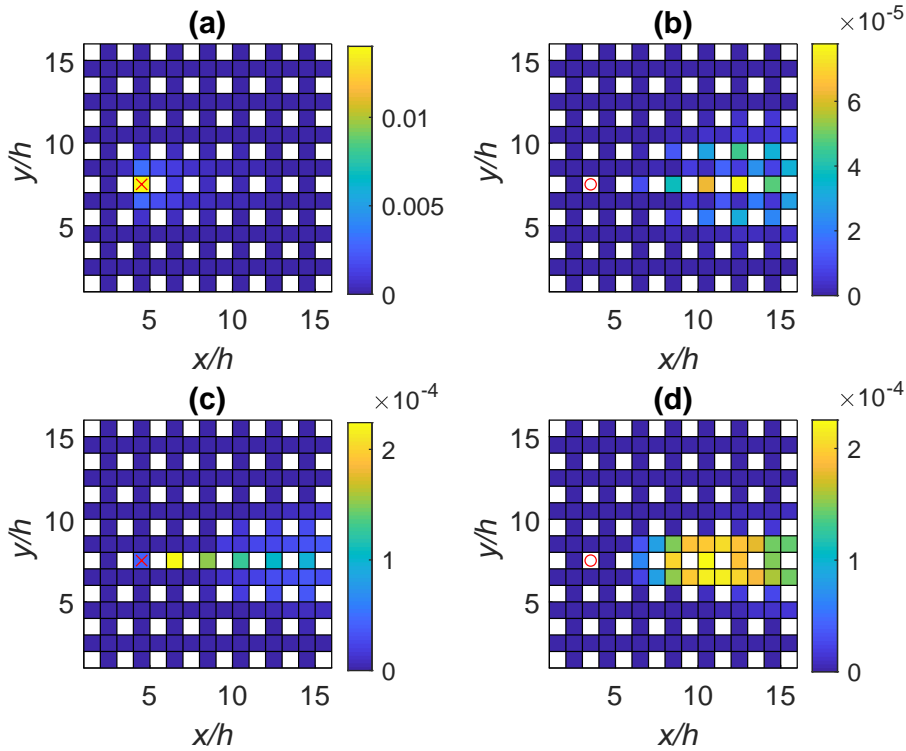
298 The magnitude of the detrainment and entrainment across the canopy top can  
 299 be quantified by computing the vertical flux (mean plus turbulent), decom-



**Fig. 4** Magnitudes of ensemble-averaged mean concentration at different distances along the forcing direction for (a) the ground source, (b) the elevated source, for the  $0^\circ$  run. Squares denote locations within the array at  $z = 0.5h$  and circles locations above the array at  $z = 1.5h$ . Filled symbols correspond to lateral locations at  $y = 6.5h$  and empty symbols at  $y = 7.5h$  respectively. (c) Ratio of absolute difference to sum of concentrations within and above each street,  $\Delta C / \Sigma C$ , for the ground source (arrows up) and elevated source (arrows down). Filled and empty symbols as for (a) and (b).



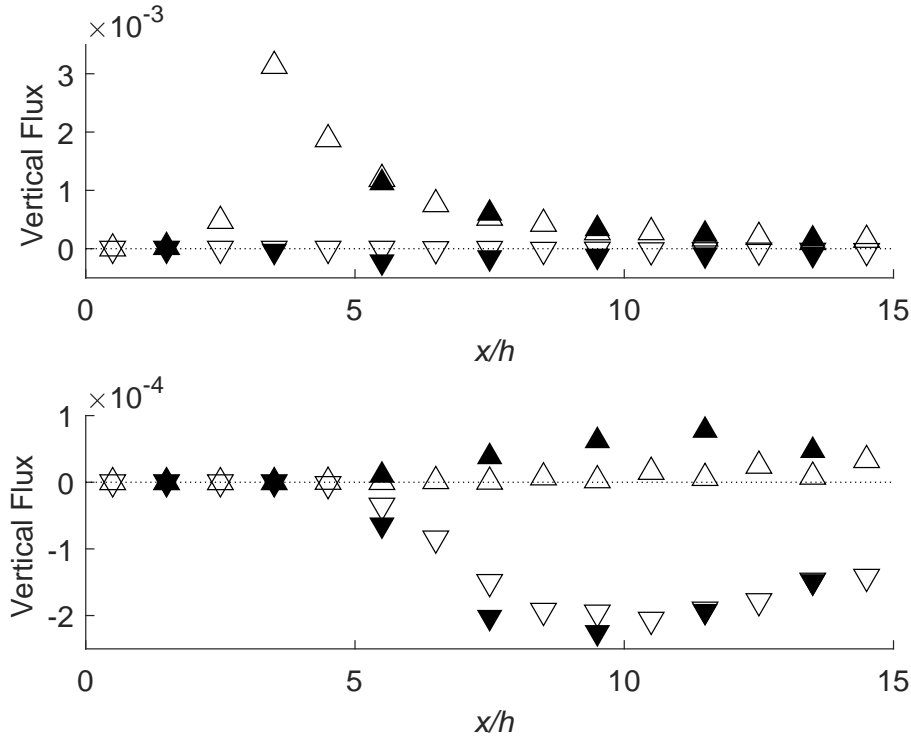
**Fig. 5** (a) Map of ensemble- and box-averaged mean concentration and (b) magnitudes of ensemble-averaged mean concentration at different distances along the plume centreline for the  $45^\circ$  run. The colour bars correspond to the common logarithm ( $\log_{10}$ ) of the concentrations. Filled symbols indicate concentrations within the array at  $z = 1.5h$  and empty symbols concentrations above the array at  $z = 0.5h$ . Location of ground source at  $z = 0.0625h$  is denoted by a red cross in (a).



**Fig. 6** Magnitude of facet-averaged vertical flux through the canopy top (a) and (b) upward, and (c) and (d) downward, for the ground source (left panels) and elevated source (right panels) for the  $0^\circ$  run. Locations of ground source at  $z = 0.0625h$  and elevated source at  $z = 2h$  are denoted by red crosses and circles respectively.

300 posed into upward and downward components respectively. Fig. 6 shows a map  
 301 of this upward and downward flux for both sources, with an average value cal-  
 302 culated over the top surface of each box at  $z = h$ . For the ground source there  
 303 is a disproportionately large upward flux over the source location and in the  
 304 adjacent channels (Fig. 6a). Hence, there is strong initial detrainment in the  
 305 immediate vicinity of the source. Upward fluxes decrease monotonically with  
 306 distance from the source (see also Fig. 7). Re-entrainment is maximum in the  
 307 very next canyon downwind of the release (Fig. 6c). Thereafter, its magnitude  
 308 decreases monotonically over subsequent canyons. Re-entrainment fluxes are  
 309 much lower over the adjacent channels. Interestingly, there is a small amount  
 310 of downward flux even in the canyon in which the source is located.

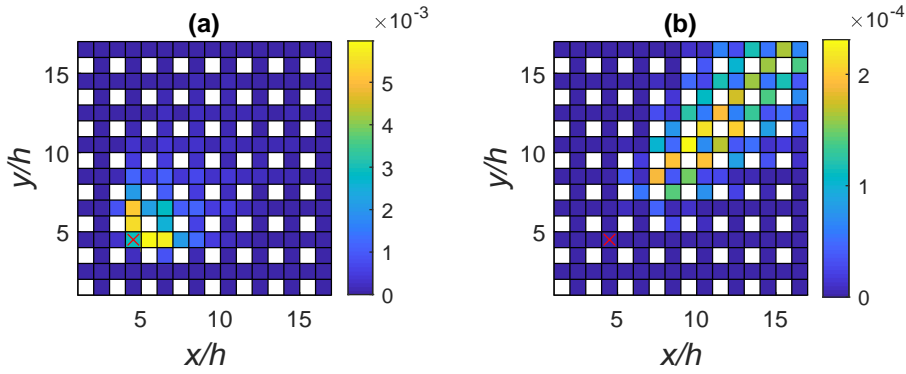
311 For the elevated source, both the upward and downward fluxes span a more  
 312 extended area. Fig. 6d shows that the downward (entrainment) flux over both  
 313 canyons and channels increase to a maximum distance of  $7h$  downstream of  
 314 the source before gradually decreasing. This is a consequence of the opposite  
 315 effects of the plume above the array growing wider to reach the top of the  
 316 array and diluting in concentration as it continues to grow. Fig 6b shows that



**Fig. 7** Facet-averaged vertical flux through the canopy top at different distances along the mean wind direction for (a) the ground source, (b) the elevated source, for the  $0^\circ$  run. Upward fluxes are denoted by upward-pointing triangles and downward fluxes by downward-pointing triangles. Filled symbols correspond to lateral locations at  $y = 6.5h$  and empty symbols at  $y = 7.5h$  respectively.

317 as soon as material has been entrained into the network, some of it is detrained  
 318 back into the air above. Mirroring the behaviour of the downward flux, the  
 319 upward flux over canyons first increases to a maximum, then decreases again.  
 320 The location of the maximum is one canyon downstream of the location of  
 321 maximum entrainment, at a distance of  $9h$  from the source. The upward flux  
 322 over channels is small in comparison, and is larger between cubes.

323 Fig. 7 shows the facet-averaged vertical flux through the canopy top as a  
 324 function of distance along the mean wind direction at lateral locations  $y = 6.5h$   
 325 and  $y = 7.5h$  for the ground source (Fig. 7a) and the elevated source (Fig. 7b).  
 326 Again, these locations were chosen because most of scalar is channelled along  
 327 the unobstructed streets adjacent to the source location. The fluxes have been  
 328 decomposed into an upward component (arrow up) and a downward compo-  
 329 nent (arrow down). Once again the flux due to the initial detrainment from  
 330 the canyon where the ground source is located (at  $z = 4h$ ) is off the scale at  
 331 0.014, compared to the value of 0.0031 in the channel adjacent to it. There-  
 332 after, the upward fluxes from the canyons and the adjacent channels are of a  
 333 similar magnitude. As already pointed out, the downward (entrainment) flux



**Fig. 8** Magnitude of facet-averaged vertical flux through the canopy top (a) upward, and (b) downward, for the  $45^\circ$  run. Location of ground source at  $z = 0.0625h$  is denoted by a red cross.

is only appreciable over the canyons for this configuration. It has a maximum value over the very next canyon from the source, decreasing monotonically thereafter. For the elevated source, the downward fluxes over the canyons and channels have a comparable magnitude, except close to the source, at  $x = 6h$ , where the flux over the canyon has a magnitude twice that over the adjacent channel. Thereafter, they rapidly converge until they are virtually identical at  $x = 12h$ . Overall, the downward flux from the elevated source increases sharply over a distance of  $5h$ , peaking at  $x = 10h$ , then decreases more slowly over a further distance of  $5h$ .

The spatial distribution of the main areas of detrainment and re-entrainment for the  $45^\circ$  run is shown in Fig. 8. They are more laterally extended compared to the  $0^\circ$  run due to enhanced topological dispersion. The initial wider plume in the canopy produces a more extended detrained plume above which then causes re-entrainment over a wider area downstream. This release scenario appears conducive to the contamination of the widest area among the three cases considered, although the resulting highest concentration levels would be reduced as a result.

#### 4 Evaluation of Time Scales for Scalar Transport Through the Network

The results of the previous section indicate that entrainment into the urban street network from a source above it, and re-entrainment of material previously released within it, can both significantly alter the steady-state mean concentration pattern. In this section we investigate the temporal development of the concentration. Given a sudden onset of a release, how quickly does the material propagate, via different processes, through the street network?

DNS run	$U_{wth}$	$U_{abv}$	$E$
0°	2.9	6.8	0.25
45°	1.2	3.4	0.40

**Table 1** Dimensionless advection and detrainment velocities normalised by  $u_\tau$ .

#### 359 4.1 Horizontal Advection and Vertical Exchange Time Scales

360 It is instructive to compute typical velocities and time scales associated with  
361 individual dispersion processes. This helps to determine which processes control  
362 the time evolution of a release. Different choices are possible in defining  
363 these velocities and time scales. Following Goulart et al. (2018), we define a  
364 facet-averaged advection velocity component  $\langle \bar{u}_i \rangle_k$  as an area average over a  
365 box facet  $k$  perpendicular to the component in question. A flux advection velocity  
366 is defined as the ratio between the advective flux  $\bar{c}\bar{u}_i$  through a street and  
367 the volume-averaged mean concentration  $\langle \bar{c} \rangle$  within that street. Goulart et al.  
368 (2018) also define a vertical detrainment velocity  $E$  as the ratio between the  
369 vertical turbulent flux and the difference between the volume-averaged concentrations  
370 within and immediately above a street. Advection and detrainment  
371 velocities calculated according to these definitions and non-dimensionalised by  
372 the friction velocity  $u_\tau$  are given in Table 1 for both DNS runs. The results  
373 show that the advection velocities just above the array are roughly 2 to 3 times  
374 those within for both wind directions. However, the vertical exchange velocity  
375 for the 0° run is only about a tenth of the advection velocity within the array,  
376 whereas the corresponding ratio for the 45° run is up to a third.

377 The large difference in the ratio of detrainment to advection velocities for  
378 the two wind directions has implications for the dispersion and consequently  
379 on the resulting concentrations. For instance, despite the fact that the nominal  
380 velocity above the array is larger for the 0° flow, it will transfer a smaller  
381 fraction of any scalar released within the array to above than for a 45° wind  
382 direction. Given the connection of breathability to the vertical exchange velocity  
383 (Neophytou and Britter 2005; Panagiotou et al. 2013), the detrainment  
384 velocity (which is related to the exchange velocity, though not identical in  
385 definition) is a relevant parameter for ventilation. The values in Table 1 show  
386 that, even with lower advection velocity the oblique case has higher breathability  
387 capacity and is hence more efficient in reducing the concentration within  
388 the array. This is consistent with our earlier findings.

389 An advection and a vertical exchange time scale may be defined as the  
390 ratio between a horizontal and vertical characteristic length scale and the  
391 advection and detrainment velocity respectively. For the arrays considered  
392 here, this characteristic length scale can be taken to be  $h$  in both the horizontal  
393 and the vertical directions. Values calculated from the DNS data and non-  
394 dimensionalised by the eddy turnover time  $T = h/u_\tau$  are given in Table 2.  
395 It is important to point out that these are average values both in time and  
396 in space (facet-averaged), and that some variability in actual time scales is  
397 inevitable.



DNS run	$T_{wth}$	$T_{abv}$	$T_E$
0°	0.34	0.15	4.0
45°	0.85	0.29	2.5

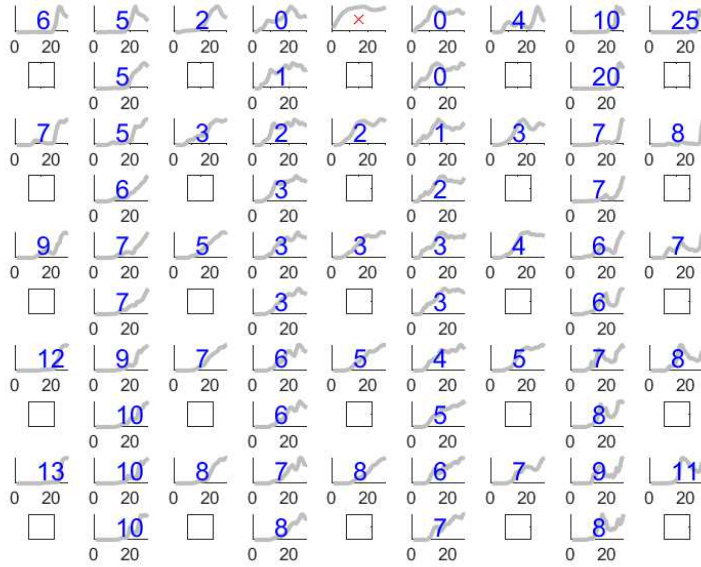
**Table 2** Dimensionless time scales associated with horizontal advection and vertical exchange.

#### 398 4.2 How Long Does It Take for a Localised Release to Reach a Given Street?

399 The typical time scales computed in the last section allow simple estimates  
400 to be made of the time it takes for a release at a given point to first reach  
401 any given street. This time is determined by the quickest pathway linking any  
402 two points in the network. We emphasize that this is an inherently transient  
403 characteristic that is subject to statistical fluctuations. In any given realization  
404 of a sudden release, the initial propagation can take any one of several paths.  
405 A large number of such realizations would then be expected to reproduce  
406 the probability of traversing these paths - the larger the ensemble, the more  
407 representative the results will be. In this section, we make use of the DNS  
408 data to estimate the minimum time to reach a given street in the network  
409 and interpret the results on the basis of the time scales computed in the last  
410 section. In the DNS the scalar release is switched on at a specific time. Hence,  
411 it is possible to track the onset and initial growth of the scalar concentration  
412 as it propagates through the street network and above. One limitation is the  
413 relatively small ensemble size in the DNS - there are 16 releases for the 45° run,  
414 12 ground source releases for the 0° run, and only 4 elevated source releases for  
415 the 0° run. Hence, the resulting ensemble averages for the latter are noisier,  
416 but still instructive enough for the purpose of providing rough estimates.

417 Fig. 9 shows a map of the non-dimensional time of first appearance of scalar  
418 concentration resulting from a ground source release in the 0° run, superim-  
419 posed on the initial part of the time series from which this time is derived.  
420 The location of the release is in the top row, middle column. The time of first  
421 appearance generally increases monotonically downstream, roughly linearly,  
422 consistent with advection being the dominant process. The exceptions are the  
423 two columns on the extreme right, close to the source. The very large values  
424 in the top right is because it is unlikely for the scalar to reach there. The  
425 left-right asymmetry is due to the small puff ensemble size. More generally,  
426 it takes much longer for the scalar to propagate laterally than streamwise for  
427 this flow direction since topological dispersion is restricted, and lateral turbu-  
428 lent diffusion is also weak (Goulart et al. 2018). Although re-entrainment does  
429 occur, particularly over the canyons aligned with the source, it does not sig-  
430 nificantly alter the time that scalar first appears because the vertical exchange  
431 time scale is so much larger than the advection time scale in the canopy.

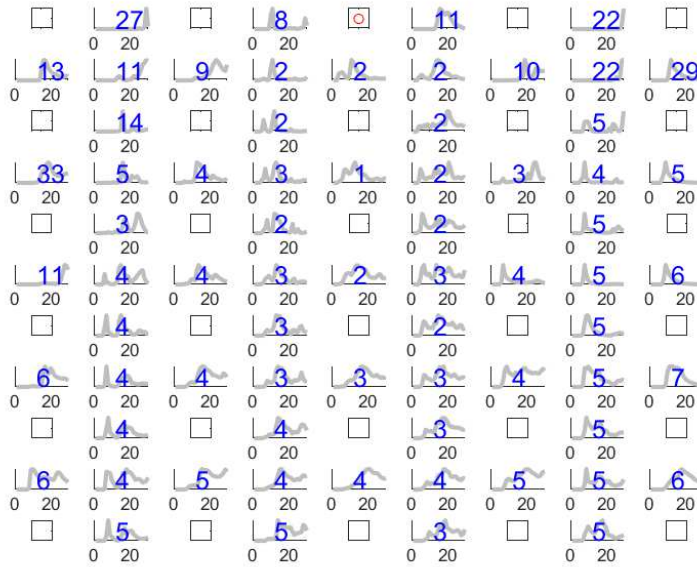
432 The corresponding results for the elevated release above the street network  
433 are shown in Fig. 10. In this case the source is located above the middle cube in  
434 the top row. In contrast to the ground release, entrainment is the predominant  
435 process here, and it modifies the times of first appearance and their distribution



**Fig. 9** Map showing non-dimensional time to reach each street for the  $0^\circ$  run for the ground source located in the middle column of the top row and denoted by a red cross. The horizontal axis has been scaled in units of the non-dimensional time and the vertical axis has been scaled by the maximum concentration in this segment of the local time series.

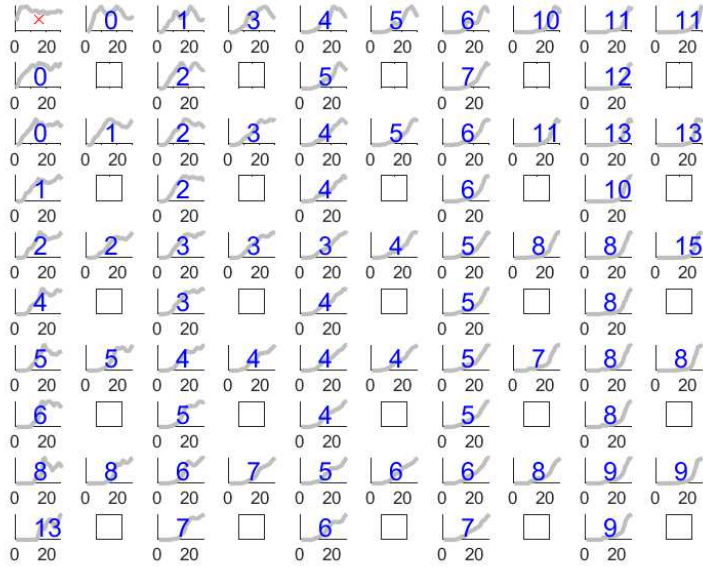
436 considerably. First, the values are much smaller than corresponding values in  
 437 Fig. 9. Propagation by entrainment is quicker than advection through the  
 438 network because the velocity above the network is much larger than that  
 439 within. The combination of entrainment and advection has the consequence  
 440 that monotonic increase of the time of first appearance with distance from the  
 441 source is not strictly respected - there are several instances where the time in a  
 442 street is lower than in any other adjacent street, i.e. local minima exist, which  
 443 are not found in the case of a ground source. Another noteworthy difference  
 444 is that the numbers are generally closer together and do not vary too much  
 445 with distance, particularly in the along-wind direction but also in the lateral  
 446 direction when compared with the ground-source release case (the exception  
 447 is in the first rows). Indeed in some instances the same value is observed over  
 448 several consecutive streets, e.g. the value 4 occurs over five successive streets,  
 449 and 5 occurs over seven streets.

450 Fig. 11 shows the distribution of first arrival times for the  $45^\circ$  run, in which  
 451 the ground source is located near the ground in the intersection at the topmost  
 452 left corner. This case is more interesting because advection and re-entrainment  
 453 both play important roles in determining the time of first arrival in different  
 454 parts of the network. The pathway that yields the quickest combination de-



**Fig. 10** As in Fig. 9 for the  $0^\circ$  run for the elevated source located at  $z = 2h$  over the middle cube in the top row and denoted by a red circle.

455 terminates this time. In delineating the dispersion pathways, it is important  
 456 to realise that a so-called ‘taxicab’ or ‘Manhattan’ geometry applies within  
 457 the street network, as opposed to normal Euclidean geometry above. In other  
 458 words, material being transported within the urban canopy is constrained to  
 459 follow the rectangular street pattern. Hence, the relevant measure of distance  
 460 is the so-called Manhattan metric given by  $d = |x| + |y|$ , in contrast with the  
 461 straight-line distance  $d = \sqrt{x^2 + y^2}$  in the unobstructed space above. This  
 462 purely geometrical factor on its own slows down scalar transport in compari-  
 463 son with the flow above. The much lower wind speed in the canopy compared  
 464 to that above is an additional factor with the same effect. The combined effect  
 465 of these two factors is that the scalar can reach a street downstream faster by  
 466 first detraining into the air above, followed by advection along the fast flow,  
 467 then re-entrainment into a downstream street, than by transport through the  
 468 network alone. Hence, it is common to find smaller values for the time of  
 469 first arrival at some streets further away than others closer to the source. For  
 470 example, the intersection at location (7, 7) in Fig. 11 registers a non-zero con-  
 471 centration after  $t = 5$  (in non-dimensional time units), compared to the time  
 472 of  $t = 6$  in the street at location (7, 1). If transport through the network were  
 473 the only pathway, then the time to reach (7, 7) should have been around twice  
 474 that to reach (7, 1). Hence, re-entrainment provides a shortcut pathway for  
 475 material to reach further downstream quicker. In an emergency response con-



**Fig. 11** As in Fig. 9 for the  $45^\circ$  run for a ground source located in the topmost left hand corner and denoted by a red cross. The mean wind direction is along the leading diagonal.

476 text, this has implications for which areas need to be attended to or evacuated  
 477 first.

## 478 5 Conclusions

479 In this paper we have investigated the dispersion patterns and propagation  
 480 from localised sources within and above an idealised street network using DNS  
 481 data, and related them to underlying dispersion processes in the network. A  
 482 summary of key results include the following:

- 483 – Detailed dispersion patterns are mapped for three different release sce-  
 484 narios: a  $0^\circ$  (aligned) wind direction with a ground source (GS) and an  
 485 elevated source (ES); and a  $45^\circ$  (oblique) wind direction with a ground  
 486 source. The spatial distribution of mean concentration is related to re-  
 487 gions of downward (detrainment) and upward (entrainment) fluxes, which  
 488 is also mapped. Widening of the in-canopy plume relative to the above-  
 489 canopy plume confirms earlier wind-tunnel observations in the literature  
 490 (DAPPLE 2011).
- 491 – Re-entrainment from a GS release occurs just a few streets downstream and  
 492 a dynamic equilibrium with detrainment is quickly established. This was  
 493 already known from the earlier studies of Goulart et al. (2018). The new

494 result here is that for an ES release entrainment also happens an equally  
495 short distance downstream but equilibration with detrainment takes much  
496 longer. There are also differences in where it happens quicker (over canyons  
497 for GS and over channels for ES).

- 498 – There are large differences between the relative magnitudes of advection  
499 and detrainment velocities for the aligned and oblique flow directions. This  
500 has implications for breathability in a street network, i.e. a change in wind  
501 direction can affect ventilation efficiency considerably.
- 502 – Characteristic advection and vertical exchange time scales are defined and  
503 compared for the different cases considered. These are used to quantify the  
504 travel times associated with different dispersion pathways and to interpret  
505 the DNS data on times of arrival of the localised release.
- 506 – The time of first arrival of the scalar in individual streets in the network is  
507 mapped for the three cases. The spatial pattern of this arrival time reflects  
508 the relative importance of different dispersion processes in each case:
  - 509 1. For the aligned flow with a GS advection through the street network  
510 is the dominant process and leads to a generally monotonic increase in  
511 the time of arrival with distance from the source. Lateral transfer is  
512 limited and this is reflected in large arrival times in lateral locations.
  - 513 2. For the aligned flow with an ES entrainment is, naturally, the dominant  
514 process. Times of arrival are much shorter than for the GS because of  
515 the faster flow above the network, and are also much more similar. Local  
516 minima in these transit times can occur.
  - 517 3. For the oblique flow with a GS there is a competition between advection  
518 and entrainment. Two factors can give the latter an advantage: the  
519 purely geometrical constraint of a taxicab geometry in the street net-  
520 work, coupled with the dynamical effect of reduced advection velocity.  
521 This can lead to material reaching remote parts of the network much  
522 faster (up to twice as fast in some cases) than it could by advection  
523 alone.

524 Taken together, these results highlight the importance of entrainment and  
525 re-entrainment as mechanisms for pollutant spread and dispersion in the urban  
526 environment. They show evidence that dispersion pathways and time scales for  
527 pollutant transport can be significantly altered as a result of these processes.  
528 This has particular implications for emergency-response modelling of toxic  
529 releases in urban areas. It can also potentially cast a new perspective on air  
530 pollution mitigation strategies, such as in the design of clean air zones and  
531 more generally in developing strategies to improve city breathability. Perhaps  
532 a key take-home message in this regard is the insight that vertical exchange  
533 is a two-way process and that the concept of exchange velocity needs to be  
534 augmented in recognition of this fact.

535 We think the results summarised above and their potential implications  
536 are important enough that further studies should be devoted to entrainment  
537 in urban canopies. In particular, it would be interesting to pursue a parameter  
538 study for different wind directions and array geometries to explore how the

539 conclusions change, perhaps using computationally cheaper methods such as  
540 large-eddy simulation or Lagrangian stochastic modelling.

541 **Acknowledgements** Fernanda Cezana, Elisa V. Goulart and Neyval Costa Reis Jnior  
542 gratefully acknowledge funding from National Council for Scientific and Technological De-  
543 velopment (CNPq), Capes (Coordination of Superior Level Staff Improvement) - Print Insti-  
544 tutional Internationalization Program (88881.311735/2018-01.) and Espirito Santo Research  
545 Foundation (FAPES), Brazil. Omduth Coceal gratefully acknowledges funding from the Nat-  
546 ural Environment Research Council (NERC) through their National Centre for Atmospheric  
547 Science (NCAS) under Grant No. R8/H12/83/002 and from the Engineering and Physical  
548 Sciences Research Council for the DIPLOS project (EPSRC Contract No. EP/K040707/1).  
549 OC also thanks the Federal University of Espirito Santo (UFES) for funding a two-week  
550 visit through their Capes.Print Institutional Internationalization Program.

## 551 References

- 552 Belcher SE, Coceal O, Hunt JCR, Carruthers DJ, Robins AG (2012) A review  
553 of urban dispersion modelling. *Atmospheric Dispersion Modelling Liaison*  
554 *Committee Report*, Tech rep
- 555 Belcher SE, Coceal O, Goulart EV, Rudd AC, Robins AG (2015) Pro-  
556 cesses controlling atmospheric dispersion through city centres. *J Fluid Mech*  
557 763:51–81, DOI <https://doi.org/10.1017/jfm.2014.661>
- 558 Branford S, Coceal O, Thomas TG, Belcher SE (2011) Dispersion of a point-  
559 source release of a passive scalar through an urban-like array for differ-  
560 ent wind directions. *Boundary-Layer Meteorology* 139(3):367–394, DOI  
561 10.1007/s10546-011-9589-1
- 562 Britter RE, Hanna SR (2003) Flow and dispersion in urban ar-  
563 eas. *Annual Review of Fluid Mechanics* 35(1):469–496, DOI  
564 10.1146/annurev.fluid.35.101101.161147
- 565 Carpentieri M, Hayden P, Robins AG (2012) Wind tunnel measurements of  
566 pollutant turbulent fluxes in urban intersections. *Atmospheric Environment*  
567 46:669–674, DOI <https://doi.org/10.1016/j.atmosenv.2011.09.083>
- 568 Carpentieri M, Robins AG, Hayden P, Santi E (2018) Mean and turbulent mass  
569 flux measurements in an idealised street network. *Environmental Pollution*  
570 234:356–367, DOI <https://doi.org/10.1016/j.envpol.2017.11.069>
- 571 Chen L, Hanga J, Sandbergc M, Claessonc L, Sabatinod SD, Wigo  
572 H (2017) The impacts of building height variations and building  
573 packing densities on flow adjustment and city breathability in ide-  
574 alized urban models. *Building and Environment* 118:344–361, DOI  
575 <https://doi.org/10.1016/j.buildenv.2017.03.042>
- 576 Coceal O, Thomas TG, Castro IP, Belcher S (2006) Mean flow and turbulence  
577 statistics over groups of urban-like cubical obstacles. *Bound-Lay Meteorol*  
578 121(3):491–519, DOI <https://doi.org/10.1007/s10546-006-9076-2>
- 579 Coceal O, Dobre A, Thomas TG, Belcher SE (2007) Structure of turbulent  
580 flow over regular arrays of cubical roughness. *Journal of Fluid Mechanics*  
581 589:375409, DOI 10.1017/S002211200700794X

- 582 Coceal O, Goulart EV, Branford S, Thomas TG, Belcher SE (2014) Flow  
583 structure and near-field dispersion in arrays of building-like obstacles. *Journal of Wind Engineering and Industrial Aerodynamics* 125:52–68, DOI  
584 <https://doi.org/10.1016/j.jweia.2013.11.013>
- 585 DAPPLE (2011) Final reports to the home office; dapple 2009/13 v3. Tech  
586 rep
- 587 Garbero V, Salizzoni P, Soulhac L (2010) Experimental study of pollutant  
588 dispersion within a network of streets. *Boundary-Layer Meteorology*  
589 136(3):457–487, DOI 10.1007/s10546-010-9511-2
- 590 Goulart EV, Coceal O, Belcher SE (2018) Dispersion of a passive scalar  
591 within and above an urban street network. *Boundary-Layer Meteorology*  
592 166(3):351–366, DOI 10.1007/s10546-017-0315-5
- 593 Harrison RM (2018) Urban atmospheric chemistry: a very special case  
594 for study. *npj Climate and Atmospheric Science* 1(1):2397–3722, DOI  
595 <https://doi.org/10.1038/s41612-017-0010-8>
- 596 Hertwig D, Soulhac L, Fuka V, Auerswald T, Carpentieri M, Hayden P, Robins  
597 A, Xie ZT, Coceal O (2018) Evaluation of fast atmospheric dispersion mod-  
598 els in a regular street network. *Environ Fluid Mech* 18(4):1007–1044, DOI  
599 10.1007/s10652-018-9587-7
- 600 Moin P, Mahesh K (1998) Direct numerical simulation: A tool in turbu-  
601 lence research. *Annual Review of Fluid Mechanics* 30(1):539–578, DOI  
602 10.1146/annurev.fluid.30.1.539
- 603 Neophytou M, Britter RE (2005) Modelling the wind ow in complex urban  
604 topographies: a computational-fluid-dynamics simulation of the central london  
605 area. In: *Proceedings of the Fifth GRACM International Congress on*  
606 *Computational Mechanics*, Limassol, Cyprus
- 607 Panagiotou I, Neophytou MKA, Hamlyn D, Britter RE (2013) City breath-  
608 ability as quantified by the exchange velocity and its spatial variation  
609 in real inhomogeneous urban geometries: An example from central london  
610 urban area. *Science of The Total Environment* 442:466 – 477, DOI  
611 <https://doi.org/10.1016/j.scitotenv.2012.09.001>
- 612 Peng Y, Buccolieri R, Gao Z, Ding W (2020) Indices employed for the assess-  
613 ment of urban outdoor ventilation - A review. *Atmospheric Environment*  
614 223:955–969, DOI <https://doi.org/10.1016/j.atmosenv.2019.117211>
- 615 Pope SB (2000) *Turbulent Flows*. Cambridge University Press, DOI  
616 10.1017/CBO9780511840531
- 617 Shen Z, Cui G, Zhang Z (2017) Turbulent dispersion of pollutants in urban-  
618 type canopies under stable stratification conditions. *Atmospheric Environ-*  
619 *ment* 156:1–14, DOI <https://doi.org/10.1016/j.atmosenv.2017.02.017>
- 620 Soulhac L, Garbero V, Salizzoni P, Mejean P, Perkins R (2009) Flow and  
621 dispersion in street intersections. *Atmospheric Environment* 43(18):2981–  
622 2996, DOI <https://doi.org/10.1016/j.atmosenv.2009.02.061>
- 623 Targa T, Kent A, Stewart R, Coleman P, Bower J, Webster H, Taylor J,  
624 Murray V, Mohan R, Aus C (2006) Initial review of air quality aspects of  
625 the buncefield oil depot explosion. AEA Technology Environment, Netcen,  
626 Tech rep
- 627