

# Air flow and pollution in a real, heterogeneous urban street canyon: a field and laboratory study

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## Abstract

In this work we investigate the influence of real world conditions, including heterogeneity and natural variability of background wind, on the air flow and pollutant concentrations in a heterogeneous urban street canyon using both a series of field measurements and controlled laboratory experiments. Field measurements of wind velocities and Carbon Monoxide (CO) concentrations were taken under field conditions in a heterogeneous street in a city centre at several cross-sections along the length of the street (each cross-section being of different aspect ratio). The real field background wind was in fact observed to be highly variable and thus different Intensive Observation Periods (IOPs) represented by a different mean wind velocity and different wind variability were defined. Observed pollution concentrations reveal high sensitivity to local parameters: there is a bias towards the side closer to the traffic lane; higher concentrations are found in the centre of the street as compared to cross-sections closer to the junctions; higher concentrations are found at 1.5 height from the ground than at 2.5 m height, all of which are of concern regarding pedestrian exposure to traffic-related pollution. A physical model of the same street was produced for the purpose of laboratory experiments, making some geometrical simplifications of complex volumes and extrusions. The physical model was tested in an Atmospheric Boundary Layer water channel, using simultaneously Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF), for flow visualisation as well as for quantitative measurement of concentrations and flow velocities. The wind field conditions were represented by a steady mean approach velocity in the laboratory simulation (essentially representing periods of near-zero wind variability). The laboratory investigations showed a clear sensitivity of the resulting flow field to the local geometry and substantial three-dimensional flow patterns were observed throughout the modelled street. The real-field observations and the laboratory measurements were compared. Overall, we found that lower variability in the background wind does not necessarily ensure a better agreement between the airflow velocity measured in the field and in the lab. In fact, it was observed that in certain cross sections, the airflow was more affected by the particular complex architectural features such as building extrusions and balconies, which were not represented in the simplified physical model tested in the laboratory, than by the real wind field variability. For wind speed comparisons the most favourable agreement (36.6% of the compared values were within a factor of 2) was found in the case of lowest wind variability and in the section with the most simple geometry where the physical lab model was most similar to the real street. For wind direction comparisons the most favourable agreement (45.5% of the compared values was within  $\pm 45^\circ$ ) was found in the case with higher wind variability but in the cross-sections with more homogeneous geometrical features. Street canyons are often simplified in research and are often modelled as homogenous symmetrical canyons under steady flow, for practical purposes; our study as a whole demonstrates that natural variability and heterogeneity play a large role in how pollution disperses throughout the street, and therefore further detail in models is vital to understand real world conditions.

Keywords: field measurements, urban air pollution, PIV, PLIF, street canyon

## 46 1. Introduction

47 Urban air quality is primarily associated with the emissions produced by traffic and industry. The actual  
48 air ventilation within urban street canyons is of rising importance mainly due to its link to the pollutant  
49 removal capacity of specific street canyons and subsequently to the long-term air pollution exposure of  
50 citizens. Street canyons, where continuous buildings flank a street on both sides, are known to be the  
51 worst type of street design in terms of pollution dispersion, especially when the background wind is  
52 perpendicular to the street. There have been many laboratory and numerical studies, and fewer field  
53 studies, of air flow and dispersion in street canyons. The Height to Width (H/W) aspect ratio of the  
54 street was shown in numerous studies to be the main geometric parameter affecting street ventilation.  
55 One or more vortices might form in the street depending on this ratio and the direction of the above  
56 roof wind (Hunter et al., 1992; Sini et al., 1996). Neophytou et al (2014) determined the exchange  
57 velocity and hence the city breathability for street canyons of different aspect ratios. In all these  
58 studies, streets are assumed to be symmetrical and homogeneous and are simplified significantly both  
59 in physical models and in simulations; the resulting air flow patterns, including a persistent vortex  
60 formation in the street, are found to be very unfavourable for ventilation and pollution removal. Yet in  
61 a numerical study of an asymmetric canyon, Assimakopoulos et al. (2003) noted that in complex  
62 geometries, such as heterogeneous canyons, the flow field could significantly differ from the flow in a  
63 symmetrical, homogeneous street canyon

64 The formation of the street canyon vortex is also dependent on the stability of atmospheric conditions  
65 (Nakamura and Oke, 1988), and on ambient wind speeds being above  $1.5 - 2\text{ms}^{-1}$  (DePaul and Sheih,  
66 1986). Real world conditions were tested also by Qin and Kot (1993), Meroney et al. (1996), and  
67 Eliasson et al. (2006), who all found that under conditions of low background wind and weaker  
68 turbulence, vortices measured in the streets were less persistent. Klein and Clark (2007) found that a  
69 small variation in the wind above the roof produced an alteration in the flow properties in the street,  
70 and a vortex could not be identified under variable wind conditions. The variability of the wind above  
71 the roof also has a significant effect in the vicinity of intersections, where small changes can  
72 substantially shift the distribution of street flow angles (Balogun et al., 2010, Klein et al., 2007).

73 It is widely recognized that background meteorological conditions have an important impact on the  
74 dispersion of pollution within and above the city (e.g. Britter and Hanna, 2003; Li et al., 2009; Gu et al.,  
75 2011). However this relationship is not always clear. Reynolds (1996), reports that there was no linear  
76 relationship between concentration levels and background meteorological conditions. The effects of  
77 alterations in the wind flow patterns in the street considerably modify the local pattern of pollutant  
78 dispersion near the intersection or in the street. As a consequence of the variability in flow structure, it  
79 is estimated that measured concentration levels might differ from predictions (Mavroides et al., 2007).  
80 Schatzmann et al. (2000) carried out a field campaign in Hanover/Germany and showed that the  
81 concentrations reduced or increased depending on whether the background wind was perpendicular,  
82 oblique or parallel to the street canyon. In addition, Karra et al. (2011) showed that near the ground the  
83 concentrations are more affected by the location of the traffic lane than the meteorological conditions.  
84 Different measures to quantify the pollutant removal capacity have been proposed, such as the  
85 breathability (Neophytou and Britter 2005; Panagiotou et al. 2013; Neophytou et al. 2014) and mean  
86 age of air (Ramponi et al. 2015; Buccolieri et al. 2015). The concept of an “exchange” velocity has also  
87 been used in the literature, e.g. an air-exchange velocity which takes into account only the air-flow rate  
88 going in and out of a defined control volume (e.g. Bentham and Britter 2003; Li et al. 2005; Moonen et  
89 al. 2011; Panagiotou et al. 2013) or a pollutant-exchange velocity which takes into account also the  
90 distribution of pollutant concentration (Liu et al. 2005; Cheng et al. 2008, Kubilay et al, 2017).

91  
92 Most of the street canyon studies reported above include comparisons between laboratory and  
93 simulations. Wind variability is largely acknowledged as an important factor in the differentiation of real  
94 field studies relative to laboratory studies or simulations under controlled conditions. However, there is  
95 only one reported study to our knowledge that compares a study under real field conditions with  
96 laboratory experiments: Blackman et al (2015), who studied the flow field inside an idealized  
97 (symmetrical and homogeneous) street canyon. Although they do not report any observations on the  
98 field wind variability, they found that overall agreement between lab and field results falls within 20%.

99 This paper addresses the issues that arise in “real” street canyons, of heterogeneity and of background  
100 wind variability, which are typically neglected in street canyon studies, to demonstrate that the situation  
101 in real streets is far more complex than expected. The real street conditions are fully investigated by  
102 drawing on a complementary set of information from both field measurements of airflow and dispersion  
103 inside a real heterogeneous canyon, and laboratory simulations of a reference case of steady,  
104 perpendicular flow in a physical model of the street, accounting for the large scale geometric complexity  
105 in the model. The field measurements of air flow and of traffic-related Carbon Monoxide concentrations  
106 were carried out in a typical Mediterranean heterogeneous street canyon in Nicosia, Cyprus, a tall  
107 narrow street with varying building shapes and heights. The laboratory experiments were carried out in  
108 a water channel, obtaining simultaneously the flow and concentrations through Particle Image  
109 Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) techniques, the simultaneous application  
110 of which has not been done for street canyon investigations to the best of our knowledge. The structure  
111 of the paper is as follows: Section 2 describes the methodologies for the field measurements and the  
112 experimental modelling, Section 3 presents observations of background wind, flow field and  
113 concentrations within the street for several wind cases, compares these qualitatively and quantitatively  
114 with the laboratory measurements, and discusses the effects of street geometry on the 3D flow field,  
115 and the effect of variable wind conditions. Finally, Section 4 presents Conclusions.

## 116 **2. Methodology**

### 117 **2.1 Field Measurements**

118 The field measurements were carried out in a typical Mediterranean heterogeneous street canyon in  
119 Nicosia, Cyprus, Rigenis Street, a tall narrow street with varying building shapes and heights. The street  
120 is shaded at that time of the day and upwards vertical velocities were not observed, thus buoyancy  
121 effects related to solar heating are not relevant. Rigenis Street is a one-way street with a South-East to  
122 North West orientation, is 160m long (L) and 8m wide (W) including the pavements, and has flat building  
123 roofs. The mean aspect ratio of the street is  $H/W=1.25$ . The South side of the street is 9.7m high on  
124 average with large variations in height up to a maximum of 11.5m. The North side is 9.9m high on  
125 average, has a mostly homogeneous building geometry and several gaps between buildings (**Figure 1a**).  
126 As seen in **Figure 1(b)**, some parts of the street have large architectural features such as balconies,  
127 which extend about a metre into the street. Morphological data was obtained from the Nicosia Master  
128 plan and the Department of Land and Surveys, Cyprus Ministry of the Interior.

129  
130 **Figure 1:** Rigenis Heterogeneous Street Canyon

131 a) Schematic Diagram of Rigenis Street and of telescope mast positions in the street at three different cross sections along the  
132 length of the heterogeneous street, b) Rigenis Street View, showing the parked cars along the South side and traffic lane on the  
133 North side. The buildings are complex and have large balconies as well as variations in roof height

134

135 Reference data on background meteorological conditions were measured every second and averaged to  
136 a one-minute resolution on top of a mast on the roof at a height of 26m ( $2H_{\text{building}}$ ) from the ground,  
137 using a La Crosse Technology WS-3502 cup anemometer and a mini weather station, at a resolution of  
138 0.1m/s and 22.5 degrees for wind direction. Velocities in the street were measured with one 3D 8100  
139 Young ultrasonic anemometer (accuracy for wind speed was  $\pm 0.1\%$  rms,  $\pm 0.05\text{m/s}$  and for wind direction  
140  $\pm 2^\circ$  for wind speeds up to 30m/s, sampled at 32Hz), and four 2D Gill Windsonic Ultrasonic Wind Sensors  
141 (accuracy for wind speed  $\pm 2\%$  and for wind direction  $\pm 3^\circ$  up to 12m/s, sampled at 1Hz.).

142 Carbon Monoxide (CO) was chosen as an indicator of traffic related emissions within the street canyon  
143 because it has slow chemical transformation within the atmosphere and can be considered inert over  
144 short distances. The main source of CO was emissions from a continuous stream of cars and vans along  
145 the street. CO concentration was measured every 10 seconds via two types of electrochemical sensors,  
146 Learian Micro ICOM and Wireless Bracelet Nodes (see Shum et al, 2013).

147 Vertical profiles of flow fields and CO concentrations were measured at three cross sections of the street  
148 (noted in **Figure 1a**), with different local street geometry as follows. Building ratios are calculated  
149 assuming south-westerly perpendicular background wind:

- 150 • Section I: building ratio  $H_{\text{leeward}}/H_{\text{windward}} = 1$ , with surrounding buildings on the South side up to  
151 27% taller and a wide gap between the buildings on the North side, and large balconies
- 152 • Section II: building ratio = 1.92, and gaps near the buildings on both sides
- 153 • Section III: building ratio = 1.28 and a gap on the South side, and large balconies on the facades  
154 on both sides of the street

155 To create the vertical profiles, the 3D and 2D anemometers and four CO sensors were spaced out along  
156 the telescopic mast, which was placed about 0.8 m away from the buildings and was gradually extended  
157 from the ground up to 12m height with a total capture time of 10 minutes for each profile. The  
158 measurements of vertical profiles were taken from 09:00 am until 12:30 pm, a time of day with  
159 relatively stable wind and traffic conditions. At each section, vertical profiles were obtained first on one,  
160 then the opposite side of the street after a 20 minute break between profiles for instrument set up.

161 A second field campaign was carried out, in which CO concentration levels were measured at street level  
162 on several days between 8:00am until 4:00pm. These CO sensors were deployed at the cross sections  
163 on both sides of the street, roughly 0.1m away from the building walls; six were positioned at a height of  
164 1.5m from the ground, six at 2.5m from the ground.

## 165 **2.2 Physical Modelling**

### 166 **2.2.1 Water Channel**

167 The physical modelling was carried out in a low-turbulence atmospheric boundary layer water channel  
168 in the Pat Kemp Fluid Mechanics Laboratory at the Dept. of Civil Engineering at University College  
169 London (UCL). This open water channel is made of a level glass bed with connecting plate glass side  
170 walls, built onto a substantial cast iron main girder structure. The dimensions of the water channel are  
171 shown in **Figure 3**. To reduce undesirable turbulence at the inlet of the channel, the water is passed  
172 through five meshes and a shaped inlet fairing. The maximum water depth that can be reached is  
173 0.22m, which was set as constant for all the simulations.

174 The maximum height of the physical model within the channel should be 40% of the depth of the  
175 boundary layer (or, the height of the free stream should be at least 2.5 the height of the scaled  
176 buildings). To create a suitable profile for a typical Urban Boundary Layer, it was necessary to increase  
177 the boundary layer thickness. A trip wire of 2mm diameter was placed at the inlet of the water channel,

178 on the floor and side walls,. **Figure 2a** shows the development of the boundary layer profile of the  
179 empty water channel with and without the trip wire at 2.30m from the inlet and shows that the  
180 boundary layer thickness (BLT) without the wire is 40mm (calculated following Hansen (1930)) while  
181 with the wire the BLT reaches a depth of 60mm. The greater boundary layer thickness allowed us to  
182 introduce a larger scale model to better visualise the flow and the tracer dye dispersion inside the  
183 canyon. **Figure 2b** shows the development of the boundary layer and the fact that once it is developed,  
184 it remains stable. As a result the scaled model was sized to be up to 60mm high. Thus, the upstream  
185 bulk velocity of the empty water channel was 0.16m/s, resulting in a Reynolds number  $3.5 \times 10^5$  at a  
186 distance of 2.30m downstream of the inlet The similarity criteria suggested by Meroney et al. (1996),  
187 Hoydysh et al. (1974) and Snyder (1972) are satisfied in our experimental set up: The Re number at the  
188 cavity exceeds 3400 and the critical roughness Reynolds number, which depends on the roughness of  
189 the plate, is greater than 2.5. Full details of the physical model and boundary layer flume are provided  
190 in Karra (2012).

191  
192 **Figure 2: a)** Velocity profile with and without trip within empty water channel, b) Development of Boundary Layer Profile within  
193 the water channel

### 194 **2.2.2 Street Canyon Model**

195 Following the previous measurements the upstream bulk velocity at  $2.5H_{\text{building}}$  from the bottom of the  
196 bed was a constant 0.23 m/s and a Reynolds number above the buildings of  $6.3 \times 10^4$ . A 1:183 scale  
197 perspex replica of the Rigenis street canyon was placed in the water channel 2.24m from the inlet, such  
198 that the flow was perpendicular to the buildings, as shown in **Figure 3**. The street replica was the only  
199 region of interest for the purposes of this study; it was simplified to represent the large scale geometric  
200 shape of the buildings and thus features smaller than 1m scale, such as balconies, were not explicitly  
201 modelled. The street replica was aligned perpendicular to the flow and spanned across the water  
202 channel up to the walls, to avoid side wall effects. Three homogeneous roughness blocks of the same  
203 height and width were positioned upstream and two similar homogeneous roughness blocks were  
204 positioned downstream of the test street canyon in order to smooth the turbulence and to achieve the  
205 necessary fully developed urban boundary layer profile.

206 **Figure 3:** Configuration of the street canyons and Rigenis street model in the water channel and PIV and PLIF set up

### 207 **2.2.3 Line Source Design and Imaging**

208 A line source released dye to simulate the exhaust emissions from vehicles aligned along the street  
209 length. The design of the line source was based on that proposed by Meroney et al. (1996) with some  
210 modifications to enable application to water properties. Rhodamine 6G was chosen as a passive scalar  
211 and was injected through the line source placed at the bottom of the canyon at a constant flow rate,  
212 8ml/min, through a syringe pump. Full description of the set up and the techniques are given by Karra  
213 (2012).

214 The study collected simultaneous measurements from PIV and PLIF, providing detailed two-dimensional  
215 information on velocity and concentrations at the three cross sections of the street canyon. The Laser  
216 system, a New Wave MiniLase double pulse Nd: YAG laser (532nm wavelength, power 100 mJ and pulse  
217 width 6ns) from TSI was placed vertically on top of the water channel at 0.70m from the bed surface up  
218 to the edge of the lens, and two CCD cameras were oriented perpendicular to the laser on both sides of  
219 the water channel and were connected to the laser pulse 610035 synchroniser to ensure that all  
220 components operated in the correct sequence. A TSI PowerView Plus 2048 x 2048 pixel CCD camera

221 was used with a Nikon 60mm lens of 2.8D focal length for the PIV and a TSI PowerView Plus 1280 x 1960  
222 pixel with 28mm Nikon lens of 2.8D focal length was used for the PLIF (Figure 2).

223

### 224 **3. Results and Discussion**

#### 225 **3.1 In-street airflow patterns for different background wind conditions**

226 The presentation of the results in this field study is structured according to background wind direction in  
227 relation to the street canyon axis as observed at rooftop level. We first present the overall variability  
228 found in the field and identify several Intensive Observation Periods (IOPs) with different background  
229 wind conditions. We then present results for the different types of IOPs.

##### 230 **3.1.1 Variability of the background wind**

231 Overall it was observed that the approaching wind above the heterogeneous canyon varied significantly  
232 throughout the daily observation period of eight hours, as seen in **Figure 4**. It was thus necessary to  
233 identify shorter duration IOPs during which the mean wind direction was relatively stable. A mean  
234 approaching wind direction was identified, as was its associated mean wind meandering (standard  
235 deviation from the mean direction), for several different IOP cases in the overall field study. Table 1  
236 shows the five identified IOPs, as classified according to the measured Mean Wind Direction, of the  
237 background wind approaching at rooftop level. The street orientation is SE to NW (135° to 315°), and  
238 the background wind would have been exactly perpendicular to the street if it had approached from  
239 225°(SW) or 45° (NE). We first discuss the cases of perpendicular wind, for both steady wind (IOP1, 2)  
240 and highly variable wind (IOP3, 5); then present the case for oblique background wind (IOP4).

241

242 **Figure 4:** Variability of reference background wind direction and velocity at 26m above the ground level: (a) perpendicular case;  
243 (b) oblique to perpendicular case (data recorded and averaged to one minute)

244

245

246 **Table 1:** Description of the five distinct Intensive Observation Periods (IOP cases).

247

##### 248 **3.1.2 Perpendicular prevailing wind and comparison with Laboratory model**

249 Two IOPs were obtained in the field for a perpendicular South-Westerly prevailing background wind.  
250 IOP1 has a mean wind variability of 26.9° and in this time period vertical profiles were obtained for  
251 Section I. IOP 2 had higher variability of 37.6° and in this time period vertical profiles were obtained for  
252 Section II. The flow fields for the same sections under perpendicular steady flow conditions were  
253 obtained in the Laboratory. The results of these observation periods are shown in **Figure 5**, and are  
254 compared to the corresponding laboratory measurements. The figure shows the direction of the  
255 prevailing wind whilst the vertical profiles were being obtained, separately for each profile, and notes  
256 the direction of the reference flow in the laboratory. As the four different vertical profiles were  
257 obtained one by one, the wind had changed during the observation period and this is noted on the side  
258 of the figures.

259 In IOP 1, Section I, wind speeds were observed overall to be 60% lower on the Northeast side of the  
260 street – which was the windward side in this case - than on the Southwest side. The typical clockwise  
261 vortex expected to arise in street canyons is seen very clearly in the laboratory model in Section I under  
262 steady flow conditions. However, this vortex was not observed in the field study.

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266

267 **Figure 5:** Reference background wind captured over the duration of recording vertical profiles in Section I and II  
268 a) Section I, IOP1: i) wind measured during the vertical profile on the South side ii) velocity fields obtained in the field and  
269 underneath those the reference velocity fields obtained via PIV in the experimental model of the street iii) wind measured  
270 during the vertical profile on the North side  
271 b) Section II, IOP2: i) wind measured during the vertical profile on the South side ii) velocity fields obtained in the field and  
272 underneath those the reference velocity fields obtained via PIV in the experimental model of the street (the grey shaded area  
273 represents a region of the street that was not visible to the PIV) iii) wind measured during the vertical profile on the North side  
274

275 Section II has a complex geometry, due to the “step down” geometry created locally by the drop in  
276 building height on the windward side, as well as the gaps around the buildings. The reference flow field  
277 observed in the Laboratory does not develop a vortex. This is due to the flow being fully three  
278 dimensional at this cross section, and this illustrates the very localised nature of the effect of geometry  
279 on airflow in the street. This three dimensional flow was seen clearly in the laboratory under steady  
280 flow conditions (as further discussed in section 3.3.2), but in the observation period IOP2, under realistic  
281 variable wind conditions the vertical profile observations do not match those obtained in the  
282 Laboratory. It is clear from the results in both sections, that real world conditions are so variable that  
283 the vortex flow, which is the hallmark of street canyon research and the main reason street canyons are  
284 considered unfavourable for ventilation, does not always appear. This is an encouraging result in terms  
285 of street ventilation.

286

### 287 **3.1.3 Highly Variable wind**

288 Flow fields were observed at Section III of the street canyon for two cases: IOP3, where there is  
289 perpendicular wind both from NE and from WSW (coming from the opposite side of the street  
290 compared with the reference case), is shown in Figure 6a; and IOP5 for highly variable wind that  
291 fluctuates from perpendicular to parallel in the observation period is shown in **Figure 6b**. (Note: during  
292 the measurements in Section III we did not observe a perpendicular prevailing wind comparable to the  
293 ones experienced for Section I and Section II, thus a laboratory reference case is not shown here; for  
294 reference it can be seen in **Figure 11**). In the cases of highly variable wind under realistic field  
295 conditions it was not possible to observe a vortex formation at all. The airflow pattern is not much  
296 different than in the case where flow was relatively steady and perpendicular. It is seen that in reality,  
297 the relative steadiness of the background wind does not seem to have a great effect on the in-street  
298 airflow and the conditions on the ground.

299  
300 **Figure 6:** Variable wind cases, vertical profiles captured in the field in Section III:  
301 a) IOP3: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles  
302 of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West  
303 b) IOP5: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles  
304 of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West side  
305

306

### 307 **3.1.4 Oblique wind**

308 Measurements were also taken in Sections I and II of the street for IOP4, in which case the prevailing  
309 approaching wind was oblique to the street axis (**Figures 7a and 7b**). The wind was relatively stable  
310 during the capture period of the profiles in both cross-sections. Yet the flow fields were quite different  
311 from what is predicted in the literature (e.g. Oke, 1998). The measured airflow patterns on the SW side  
312 of the street are quite similar for both cross sections, which have very similar background wind  
313 conditions in the field. However, the measurements are quite different on the NE side of the street,

314 which in Section II, produces a “step-down” geometry. This illustrates the effect of heterogeneity of the  
315 street on the flow fields.

316 **Figure 7:** Oblique wind - vertical profiles captured in the field during IOP4:

317 a) Section I: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical  
318 profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West  
319 side

320 b) Section II: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical  
321 profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West  
322 side

323

324

### 325 **3.2 Quantitative comparison between velocities in the lab and field measurements**

326 A quantitative comparative analysis was conducted for the air flow velocity fields obtained in the urban  
327 field measurements and the corresponding laboratory simulations, in order to assess quantitatively the  
328 degree of influence on the flow velocity fields due to the real field conditions as opposed to those in a  
329 controlled physical simulation in the lab. This was conducted only for the IOP cases IOP1 and IOP2 - for  
330 relatively stable perpendicular background wind. The corresponding laboratory velocities were  
331 normalized through the Reynolds number similarity. This analysis was carried out following the  
332 methodology used by Neophytou et al. (2011) for comparing urban field measurements and  
333 corresponding numerical simulations in the Joint Urban 2003 field campaign in OKC- U.S.A.

334

335 For a collective view of IOP cases IOP1 and IOP2, **Figure 8** shows the scatter plots of the wind direction  
336 and wind speed as observed in the field in comparison with the laboratory measurements. The dotted  
337 lines in the figures depict the bounds of interest within which the variability is assessed; for the wind  
338 direction the bounds are set within 45°, while for the wind speed the bounds are set for values within a  
339 factor of 2 (i.e. between 1/2 and 2). The figures distinguish amongst measurement points located at  
340 different sides of the street canyon (NE versus SW side). The total fraction of the measurement points  
341 falling within the bounds is calculated. **Table 2** presents these fractions in terms of the assessed IOP  
342 cases IOP1 and IOP2, which refer to observation periods at cross-sections I and II respectively.

343 We observe that lower wind variability does not necessarily ensure a better agreement between the  
344 wind direction measured in the field and in the lab. This is consistent with the findings in section 3.1. As  
345 seen in **Table 2**, only a 27.3% fraction of the wind direction measurements at cross section I (IOP1) was  
346 found to be within  $\pm 45$  degrees of the corresponding laboratory measurements despite having lower  
347 variability in the mean rooftop wind direction (26.9), while at cross section II (IOP2), the corresponding  
348 fraction was found to be 45.5% and the variability was (37.6). It may also be that the airflow was much  
349 more affected by the particular local street features and complex architectural features in cross section  
350 I, which had building extrusions and large balconies that were not present in the simplified physical  
351 model tested in the laboratory.

352

353 Regarding the wind speeds, the situation is reversed: for IOP1 a 36.6% fraction of the wind speed data  
354 from the field measurements and the corresponding laboratory measurements was found to be within a  
355 factor of 2 agreement, whereas a smaller fraction, of 22.7 %, falls within a factor of 2 for the IOP2 case.  
356 The lower agreement for IOP2 (compared to IOP1) persists when we re-consider the fraction for the  
357 wind speeds only above a threshold value of 0.05m/s, which is the threshold value of the  
358 instrumentation. It is interesting that the case with the lower agreement (IOP2) takes place at Section II,  
359 which is more homogeneous and has less obstructions and architectural features compared to the other



360 sections, but which is a “step-down” configuration in which a vortex would not be expected to form, and  
361 has not been formed in the laboratory.

362  
363 The data is also calculated and presented in **Table 2** in terms of the Windward or the Leeward side of  
364 the street canyon. The Windward side of the street-canyon shows a better agreement than the Leeward  
365 side of the street-canyon for the wind direction, but no marked difference in agreement for the wind  
366 speeds. It must be noted however that the fraction of measurements above the accuracy threshold is  
367 substantially lower on the windward side (only 7.7%) therefore this result may not be conclusive yet and  
368 merits further testing in future field campaigns.

369  
370 **Figure 8:** Scatter plots for (a) the wind direction measurements and (b) the wind speed measurements as observed in the field  
371 measurement campaign and in the corresponding laboratory measurements for two observation periods - IOP1, IOP2.: i) IOP1  
372 is at Section I ( $H_l/W=1.12$ ,  $H_w/W=1.12$ ), and ii) IOP2 is at Section II ( $H_l/W=1.25$ ,  $H_w/W=0.75$ ), The plotted dotted lines show the  
373 bound lines within  $\pm 45^\circ$  (for wind direction) and within a factor of 2 (for wind speed)

374  
375 **Table 2:** Fraction of points included within the bounds for IOP I and II – calculated separately for section I, section II and for the  
376 Windward side in both sections and the Leeward side in both sections

377

### 378 **3.3 Pollution Distribution**

#### 379 **3.3.1 Relationship between street level CO concentrations and background wind direction**

380 Carbon Monoxide was measured during along the length of the street. First, results of a measurement  
381 period of one hour in Section II, in the middle of Rigenis street are shown. **Figure 9** shows the CO  
382 concentrations at one minute averages at a height of 1.5 metres from the ground in the middle section  
383 of Rigenis street canyon as a function of rooftop wind direction (wind from the north corresponds to  $0^\circ$   
384 and wind perpendicular to the street corresponds to  $225^\circ$ ) for a measurement period of one hour.  
385 Within this one hour, the wind meandered between predominantly perpendicular, oblique and parallel  
386 to the street. It can be seen that there is no wind direction that is clearly associated with higher  
387 pollution episodes. This variability is consistent with the results of the velocity measurements, and is  
388 determined by the full set of parameters influencing the street, such as the variation in wind speed and  
389 traffic levels in the street at the time of the measurements. Overall, the wind variability in real field  
390 conditions is so high that background wind direction at rooftop height does not dominate the pollution  
391 concentrations in the street.

392  
393 **Figure 9:** Relationship between CO levels and wind direction in Section II; shown on the left are results observed on the South  
394 West side and to the right, results from the North East side of the street. The measurements for perpendicular wind to the  
395 street episodes and for parallel wind episodes are noted on the figure.

396 The following results are from a second field campaign in which CO concentration levels were measured  
397 at street level on several days between 8:00am until 4:00pm. Concentration levels were measured at  
398 several locations along the street length, as seen in the diagram in Figure 10b. **Table 3** presents the  
399 second set of IOP cases, showing the eight hour average background wind conditions recorded on the  
400 rooftop, during the campaign.

401

402 **Table 3:** IOP cases for pollution dispersion measurements

403

404 **Figure 10a** presents the mean CO concentration levels for each IOP case. These are averaged from all  
405 measurements along the length of the street at heights of 1.5m, and 2.5m from the ground. Because of

406 the high variability of the wind, results are shown for the time period within those eight hours of  
407 measurements in which steadier conditions occurred.

408 On the whole, for all IOP cases the CO concentrations are greater in the middle of the canyon, Section II,  
409 as compared with Sections I and III, which are nearer the junctions at the ends of the street. The only  
410 exception is the high concentrations observed in Section III at 1.5 m height on the SW side of the street.  
411 This site is unique as there are no gaps in the street canyon near that measurement location and this  
412 might explain the higher concentrations there.

413  
414 **Figure 10:** a) Mean Concentration levels along the street for all IOP cases; (i) South West side and (ii) North West side b)  
415 Schematic diagram of measurements positions

416  
417 For all IOP cases the concentrations are systematically higher at 1.5m height by 20% to 50% than at  
418 2.5m height, demonstrating that pedestrian exposure near the ground can be significantly higher than  
419 expected from rooftop measurements.

420 For the case of persistent oblique wind in IOP4, the CO mean concentrations were lower overall by 20-  
421 30% compared to the partly oblique flow in IOP3. However, IOP presented higher concentrations in  
422 most locations than for IOP2, contrary to the expectation, in symmetrical canyons, that CO  
423 concentrations for oblique directions would be always lower than for perpendicular flow (Vachon et al.,  
424 2000). This might be as a result of the meandering of the wind during the measurement period, the  
425 specific traffic rate and levels during that period (Karra et al., 2011), or due to the heterogeneity of the  
426 street.

### 427 428 **3.3.2 Flow and dispersion in the laboratory**

429 The experimental study enabled very detailed simultaneous observations of flow and concentrations for  
430 the reference case of steady perpendicular wind under controlled conditions. **Figure 11** presents the  
431 mean velocities and concentrations at the three cross sections inside the heterogeneous street. The  
432 flow is perpendicular to the street, entering at rooftop level from the left. Great differences between  
433 the cross sections are found in both the airflow and the pollution concentrations. **Figure 11a** shows the  
434 velocity and concentration field in Section I. There is mass transfer from the windward building to the  
435 leeward building resulting in the accumulation of pollution near the wall of the leeward building. This  
436 leads to Leeward concentrations which are twice as high as those on the wall of the windward building.

437 Under the conditions of steady flow in the lab, there are robust, systematic differences in  
438 concentrations between the different sections and sides of the street. **Figure 11b** shows that Section II  
439 produces a different flow pattern than typically found in symmetrical street canyons, which results in  
440 enhanced mixing and a more homogeneous distribution of pollutants in the street. Pollution  
441 concentrations at the top of the leeward building are 60% lower than at the bottom of the canyon.  
442 Section III, seen in **Figure 11c**, shows a flow pattern that is more similar to the symmetrical canyon, due  
443 to the small ratio of  $H_l/H_w$ . Again, towards the leeward building the concentrations are twice as high as  
444 those near the windward wall. The table in **Figure 11e** presents the total mean concentration over the  
445 same domain from  $z=0\text{mm}$  up to  $z=60\text{mm}$ , for all cross sections. We find the mean concentration is  
446 lowest in Section I, followed by Section II, while Section III accumulates concentrations more than twice  
447 as high as those in Section I.

448 In the laboratory, which corresponds most closely to the field study IOP case IOP2, we observed greater  
449 concentrations always on the leeward side, as seen in **Figure 11a, 11b, 11c**. Yet, in the field, the mean

450 concentrations were always greater only on side of the street, on the NE side, for **all** IOP cases and at  
451 both measurement heights. This was true both for the case of IOP2, IOP3, and IOP4 when the NE side  
452 was the windward side, and for IOP1, when the NE side was the leeward side. Thus, this higher  
453 concentration on the NE side of the real street was in effect whether the wind was perpendicular,  
454 oblique or meandering and regardless of the direction the wind was approaching from. This indicates  
455 that maybe a local parameter in the street that did not appear in the experimental model, has a higher  
456 effect on concentrations. It is likely that this anomaly relates to the traffic lane in the real street not  
457 being exactly in the centre of the street but closer to the NE side. It may also be because of the line of  
458 parked cars on the SW side.

459 Instantaneous velocity and concentration fields (period of time from 0.0004s to 1.98s) are shown in  
460 **Figure 11d**. The vortex that can typically be seen when calculating the average values for steady flow is  
461 not seen clearly here, and observations over a time series in the experiment show this vortex dissolving  
462 and reconstructing at short intervals. This instantaneous image is a good representation of field  
463 conditions as background wind meanders or changes speed.

464  
465 **Figure 11:** Velocity and concentration fields in the heterogeneous street canyon.  
466 In the grey area, vectors and concentrations were not visible to the PIV and PLIF systems due to the higher buildings obstructing  
467 the view and velocities and concentrations could not be measured: a) Section I, b) Section II, c) Section III and d) instantaneous  
468 measurements of velocity field and concentration levels in Section II, e) **Table 4**; Mean concentration levels in heterogeneous  
469 street canyon

470 The heterogeneous street, with uneven building heights along the length of the street and gaps between  
471 buildings, shows marked three dimensional flow patterns. This can be seen clearly in **Figure 12**, which  
472 presents the velocity fields on three horizontal planes as visualised from above, at 8mm, 30mm and  
473 50mm from the bottom of the bed. There is significant channelling through the gaps in the buildings.

474  
475 **Figure 12:** Velocity fields at three horizontal planes along the length of the heterogeneous street a) at 8mm from the bottom, b)  
476 at 30mm from the bottom, c) at 50mm from the bottom, d) Position of the measurements on the model of the street canyon

477

478

479

#### 480 **4. CONCLUDING REMARKS**

481 In this work we investigate a heterogeneous real urban street canyon using a series of field  
482 measurements and controlled laboratory experiments and attempt to measure and analyse all its  
483 complexities, to account for both the real heterogeneity in the geometry and the real field conditions  
484 including great wind variability. The complementarity of the field campaign and the physical model have  
485 afforded us a deeper understanding of a wide range of issues of importance to street canyon ventilation,  
486 and have demonstrated just how complicated air flow and pollutant dispersion processes can be in real  
487 street canyons. To our knowledge, such a dataset (i.e. accounting for both the geometric complexity,  
488 the wind variability and the combination of air flow and pollutant concentrations) has not been reported  
489 so far. There is a comparative study between laboratory and field measurements over an idealized,  
490 homogeneous urban street but not in a highly heterogeneous real urban canyon. Furthermore, our  
491 study reports comparative results for both the airflow and pollutant dispersion fields – for such a real  
492 canyon; so far only airflow results have been compared in some other case studies.

493 Field measurements of wind velocities and Carbon Monoxide (CO) concentrations were taken under real  
494 field conditions in Rigenis Street in Nicosia city centre (Cyprus), at several cross-sections along the length  
495 of the street (each cross-section being of different aspect ratio). A physical model of the same street  
496 was produced for the purpose of laboratory experiments, of necessity making some geometrical  
497 simplifications of complex volumes and extrusions. The physical model of the street was tested in an  
498 Atmospheric Boundary Layer water channel, using simultaneously Particle Image Velocimetry (PIV) and  
499 Planar Laser Induced Fluorescence (PLIF), for flow visualisation as well as quantitative measurement of  
500 concentrations and flow velocities. The experiments demonstrated the effects of large scale street  
501 heterogeneity on airflows in this type of street canyon, and how they differ from those expected in a  
502 symmetrical, homogeneous street canyon. The variable wind field conditions were represented by a  
503 steady mean approach velocity in the laboratory simulation. The real field background wind was in fact  
504 observed to be highly variable; thus different intensive observation periods represented by a different  
505 mean wind velocity and different wind variability were defined. The laboratory investigations  
506 (essentially representing periods of near-zero wind variability) showed a clear sensitivity of the resulting  
507 flow field to the local geometry and substantial three-dimensional flow patterns were observed  
508 throughout the modelled street. The real-field observations and the laboratory measurements were  
509 compared for the cases of perpendicular flow observed in the field.

510 Overall, we found that lower wind variability does not necessarily ensure a better agreement between  
511 the airflow velocity measured in the field and in the lab. In fact, we believe that in certain cross  
512 sections, the airflow was more affected by the particular, local street geometry and complex  
513 architectural features such as building extrusions and balconies (which were not represented in the  
514 simplified physical model tested in the laboratory), than by the real wind field variability. For wind  
515 speed comparisons the most favourable agreement (36.6% of the compared values was within a factor  
516 of 2) was found in the case of lowest wind variability in the section closest to the physical lab model; for  
517 wind direction comparisons the most favourable agreement (45.5% of the compared values was within  
518  $\pm 45^\circ$ ) was found in the case with higher wind variability but in the cross-sections with more  
519 homogeneous geometrical features.

520 Street canyon studies are always limited by the necessity to reduce complexity of real streets when  
521 laboratory scale studies are conducted. This study is no different, and it is possible that a better  
522 agreement would have been achieved if the physical model were a more exact replica of the  
523 surrounding streets. However this study attempts to show that these complexities and heterogeneity do  
524 make a difference by accounting for large scale features and by conducting very detailed flow  
525 visualisation. Field studies in street canyons are severely limited by resources and time constraints; by  
526 necessity this study provided a snapshot of the conditions in a real street at a few particular times. It is  
527 seen that by conducting both studies, a more comprehensive picture of the airflow and pollution  
528 concentrations that can be expected in that street can be constructed, and some general observations  
529 about the impact of street heterogeneity and wind variability can be made.

530 More specifically we have found that:

531 1. Realistic wind conditions were found to be highly meandering throughout the day. This should have  
532 had a demonstrable effect on flow patterns measured in the street, on formation of the vortex, and on  
533 pollution concentrations. Yet a quantitative analysis comparing local air velocities in the field and in the  
534 lab finds low agreement even when background wind is stable, during short Intensive Observation  
535 Periods. We find that in the field, airflow patterns do not relate clearly to background wind speed,  
536 direction, and variability within an observational time period. In the laboratory, we find systematic  
537 differences in pollution concentrations between different sections and sides of the street; yet under real

538 conditions, variability in the street measurements is high. This raises questions about vortex formation  
539 in real streets and its impact on the ventilation of real streets.

540 2. The laboratory study demonstrates the effects of heterogeneity on airflow and pollution distribution,  
541 with substantial three dimensional flow patterns throughout the street, and a clear sensitivity to local  
542 geometry. The street canyon's aspect ratio as a whole does not explain the flow patterns found in this  
543 case. We find that simplification of a real street to a homogeneous street canyon in models and  
544 simulations needs to be done with caution.

545 3. As some of our field observations cannot be explained only by overall street geometry or by wind  
546 intensity and direction, it seems possible that local street parameters have a significant effect on flow  
547 and dispersion: the position of the traffic lane, the presence of parked cars and the presence of large  
548 balconies, all might affect the flow. We observe that CO concentrations are always greater on the NE  
549 side of this street, regardless of the direction of the background wind. This is most likely due to the  
550 location of the traffic lane being closer to the NE side of the street and demonstrates a high sensitivity  
551 inside the street to this local parameter.

552 4. We observe a couple of noteworthy results of the field campaign that raise issues of concern for  
553 pedestrian exposure to traffic related pollution in all types of street canyons: that concentrations are  
554 almost always higher in the middle of the street, away from the junctions. And that in all cases,  
555 pollution concentrations were systematically higher at the height of pedestrians, 1.5 m, than they were  
556 at 2.5 m height.

557

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559

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563

## 564 **References**

565 Assimakopoulos, V., Simon, H., Moussiopoulos, N., 2003. A numerical study of atmospheric pollutant  
566 dispersion in different two-dimensional street canyon configurations. *Atmospheric Environment* 37 (29),  
567 4037-4049.

568

569 Balogun, A. A., Tomlin, A. S., Wood, C. R., Barlow, J. F., Belcher, S. E., Smalley, R. J., Lingard, J. J.,  
570 Arnold, S. J., Dobre, A., Robins, A. G., Martin, D., Shallcross, D. E., 2010. In-street wind direction  
571 variability in the vicinity of a busy intersection in central London. *Boundary-Layer Meteorology* 136,  
572 489-513.

573

574 Bentham, T., and Britter, R. 2003. Spatially averaged flow within obstacle arrays. *Atmos Environ* 37  
575 (15):2037-2043.

576

577 Blackman, K., Perret, L., Savory, E., Piquet T., 2015. Field and wind tunnel modeling of an idealized  
578 street canyon flow. *Atmospheric Environment* 106 139-153

579

580 Britter, R., Hanna, S., 2003. Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics* 35,  
581 469-496.

582

583 Buccolieri, R., Salizzoni, P., Soulhac, L., Garbero, V., and Di Sabatino, S. 2015. The breathability of  
584 compact cities. *Urban Clim* 13:73-93.

585

586 Cheng, W.C., Liu, C.-H., and Leung, D.Y.C. 2008. Computational formulation for the evaluation of street  
587 canyon ventilation and pollutant removal performance. *Atmospheric Environment* 42 (40):9041-  
588 9051.

589

590 DePaul, F., Sheih, C., 1986. Measurements of wind velocities in a street canyon. *Atmospheric*  
591 *Environment* (1967) 20 (3), 455-459.

592

593 Eliasson, I., Offerle, B., Grimmond, C., Lindqvist, S., 2006. Wind fields and turbulence  
594 statistics in an urban street canyon. *Atmospheric Environment* 40 (1), 1-16.

595

596 Gu, Z.-L., Zhang, Y.-W., Cheng, Y., Lee, S.-C., 2011. Effect of uneven building layout on air flow and  
597 pollutant dispersion in non-uniform street canyons. *Building and Environment* 46, 2657-2665.

598

599 Hansen M., 1930. Velocity distribution in the Boundary layer of Submerged Plate, NACA-TM-585

600

601 Hoydysh, W. G. Griffiths, R. A. and Ogawa, Y., 1974. A scale model study of the dispersion of pollution  
602 in street canyons. *Proceedings of the 67th Annual Meeting of the Air Pollution Control Association*,  
603 Denver, CO, 9–13, APCA Paper No. 74-157

604

605 Hunter, L., Johnson, G., Watson, I., 1992. An investigation of three-dimensional characteristics of flow  
606 regimes within the urban canyon. *Atmospheric Environment Part B Urban Atmosphere* 26, 425-432.

607

608 Karra, S, Malki- Epshtein L., Neophytou, M., 2011. The dispersion of traffic related pollutants across a  
609 non homogeneous street canyon. *Procedia Environmental Sciences* 4 , 25–34

610

611 Karra, S., 2012. An Investigation of traffic related pollutants dispersion in heterogeneous street canyon.  
612 PhD Thesis, University College London United Kingdom.

613

614 Klein, P. and Clark, J. V., 2007. Flow variability in a North American downtown street canyon.  
615 *American Meteorological Society*, 851-877.

616

617 Klein, P., B. Leidl and M. Schatzmann, 2007. Driving physical mechanisms of flow and dispersion in  
618 urban canopies. *International Journal of Climatology* 27, 1887–1907

619  
620 Kubilay, Neophytou, Matsentides, Loizou, Carmeliet (2017). The pollutant removal capacity of urban  
621 street canyons as quantified by the pollutant exchange velocity. *Urban Climate* (under review)

622

623 Kumar, P., Morawska, L., 2013. Energy-pollution nexus for urban buildings. *Environ. Sci. Technol* 47,  
624 7591-7592.

625

626 Li, X.-X., Liu, C.-H., Leung, D. Y., 2009. Numerical investigation of pollutant transport characteristics  
627 inside deep urban street canyons. *Atmospheric Environment* 43, 2410-2418.

628

629 Li, X.-X., Liu, C.-H., and Leung, D.Y.C. 2005. Development of a k- $\epsilon$  model for the determination of air  
630 exchange rates for street canyons. *Atmospheric Environment* 39 (38):7285-7296.

631

632 Liu, C.-H., Leung, D.Y.C., and Barth, M.C. 2005. On the prediction of air and pollutant exchange rates in  
633 street canyons of different aspect ratios using large-eddy simulation. *Atmos Environ* 39 (9):1567-  
634 1574.

635

636 Longley, I., Gallagher, M., Dorsey, J., Flynn, M., Barlow, J., 2004. Short-term measurements of air flow  
637 and turbulence in two street canyons in Manchester. *Atmospheric Environment* 38 (1), 69-79.

638

639 Meroney, R. N., Pavageau, M., Rafailidis, S., Schatzmann, M., 1996. Study of line source characteristics  
640 for 2-d physical modelling of pollutant dispersion in street canyons. *Journal of Wind Engineering and*  
641 *Industrial Aerodynamics* 62 (1), 37-56.

642

643 Moonen, P., Dorer, V., and Carmeliet, J. 2011. Evaluation of the ventilation potential of courtyards and  
644 urban street canyons using RANS and LES. *J. Wind Eng. Ind. Aerodyn.* 99 (4):414-423.

645

646 Nakamura, Y., Oke, T., 1988. Wind, temperature and stability conditions in an eastwest oriented urban  
647 canyon. *Atmospheric Environment* (1967) 22 (12), 2691-2700.

648

649 Neophytou, M.K.-A., and Britter, R.E. 2005. Modelling the wind flow in complex urban topographies: a  
650 Computational-Fluid-Dynamics simulation of the central London area. *Proceedings of the Fifth*  
651 *GRACM International Congress on Computational Mechanics*. In. Limassol, Cyprus, 29 June-1  
652 July.

653

654 Neophytou, M., Goussis, D., Mastorakos, E., Britter, R., 2005. The conceptual development of a simple  
655 scale-adaptive reactive pollutant dispersion model. *Atmospheric Environment* 39 (15), 2787-2794.

656

657 Neophytou, M. K.-A., Gowardan, A. G., Brown, M.J., 2011. An inter-comparison of three urban wind  
658 models using Oklahoma City joint urban 2003 wind field measurements. *Journal of Wind Engineering*  
659 *and Industrial Aerodynamics* 99, 357-368

660  
661 Neophytou, M.K.-A., Markides, C.N., Fokaides, P.A., 2014. An experimental study of the flow through  
662 and over two-dimensional rectangular roughness elements: Deductions for urban boundary layer  
663 parameterizations and exchange processes. *Physics of Fluids* Vol. 26 Issue 8, p1  
664

665 Panagiotou, I., Neophytou, M. K.-A., Hamlyn, D., Britter, R. E., 2013. City breathability as quantified by  
666 the exchange velocity and its spatial variation in real inhomogeneous urban geometries: An example from  
667 central London urban area. *Science of The Total Environment* 442, 466 -477.  
668

669 Qin, Y., Kot, S., 1993. Dispersion of vehicular emission in street canyons, Guangzhou city, south china  
670 (p.r.c.). *Atmospheric Environment. Part B. Urban Atmosphere* 27 (3), 283-291.  
671

672 Ramponi, R., Blocken, B., de Coo, L.B., and Janssen, W.D. 2015. CFD simulation of outdoor ventilation  
673 of generic urban configurations with different urban densities and equal and unequal street  
674 widths. *Build Environ* 92:152-166.  
675

676 Sini, J.-F., Anquetin, S., Mestayer, P. G., 1996. Pollutant dispersion and thermal effects in urban street  
677 canyons. *Atmospheric Environment* 30 (15), 2659-2677.  
678

679 Snyder, W. H., 1972. Similarity criteria for the application of fluid models to the study of air pollution  
680 meteorology. *Bound.-Layer Meteorol.* 3, 113  
681

682 Xie, S., Zhang, Y., Qi, L., Tang, X., 2003. Spatial distribution of traffic-related pollutant concentrations  
683 in street canyons. *Atmospheric Environment* 37 (23), 3213-3224.  
684  
685