On the simulation of thick non-neutral boundary layers for urban studies in a wind tunnel

D. Marucci^{a,*}, M. Carpentieri^a, P. Hayden^a

^a*EnFlo Laboratory, Department of Mechanical Engineering Sciences, University of Surrey,
Guildford, Surrey GU2 7XH, UK*

Abstract

Stable and convective boundary layers over a very rough surface have been studied in a thermally-stratified wind tunnel. Artificial thickening by means of spires was used to accelerate the formation of a sufficiently deep boundary layer, suitable for urban-like boundary layer flow and dispersion studies. For the stable boundary layer, the methodology presented in Hancock and Hayden (2018) for low-roughness offshore surface conditions has been successfully applied to cases with higher-roughness. Different levels of stratification and roughness produced modifications in the turbulence profiles of the lower half of the boundary layer, but little or no change in the region above. Data for a stronger stability case suggested that the employed spires may not be suitable to simulate such extreme condition, though further studies are needed. The results were in reasonably good agreement with field measurements. For the convective boundary layer, great attention was given to the flow uniformity inside the test section. The selection of a non-uniform inlet temperature profile was in this case found not as determinant as for the stable boundary layer to improve the longitudinal uniformity, while the application of a calibrated capping inversion considerably improved the lateral uniformity. The non-dimensional vertical profiles of turbulent quantities and heat fluxes, did not seem to be influenced by roughness.

Keywords: Stable boundary layer, Convective boundary layer, Urban

*Corresponding author

Email address: d.marucci@surrey.ac.uk (D. Marucci)

1. Introduction

Atmospheric stratification is due to variations in temperature and humidity with height. A near-adiabatic profile of potential temperature is present in a neutrally stratified atmosphere, where vertical motions of fluid particles are neither amplified nor damped, while an unstable (or convective) stratification is characterised by an enhancement of vertical movements and stable flows are characterised by attenuated vertical motion. Stability affects the atmospheric boundary layer (ABL) depth and structure as well as velocity, temperature and turbulence profiles within it.

Non-neutral stratified conditions are frequently found in atmospheric flows. The data analysis by Argyle and Watson (2012) indicated that non-neutral conditions were present for 70% of the time in two UK offshore wind farm sites. In urban areas, a large predominance of non-neutral atmosphere was documented, for example, by Wood et al. (2010) over the city of London, UK, with convective cases happening three times more frequently than stable. Nevertheless, most of the experimental and numerical studies focus on neutral flows due to the difficulties in studying atmospheric stratification.

Some experimental studies involving stratified boundary layers (BLs) have been reported so far. The facilities used for this purpose range from water tanks (e.g., Willis and Deardorff, 1974, who simulated a convective boundary layer, CBL, by heating the water from the bottom), saline tanks (like the one in Hibberd and Sawford, 1994, in which the stratification was generated by differences in the salinity level instead of temperature) to wind tunnels. As pointed out by Fedorovich (2004), the first two techniques “omit or treat rather indirectly the effects of wind shears on the turbulence regime”, effect that may acquire even more importance when dealing with very rough surfaces, such as urban environments. Thermally-stratified wind tunnels specifically designed for the simulation of stable (SBL) and convective (CBL) boundary layers have

29 been built in the past decades. See Meroney (1998) for a review of the main
30 requirements for CBL simulation.

31 One approach to simulating non-neutral flows in a wind tunnel relies on
32 the development of the BL by means of floor cooling or heating, without any
33 mechanical thickening device. Despite being conceptually simple, such a method
34 requires a very long development region for thick BLs. For example, Arya
35 and Plate (1969) managed to get a 70 cm thick SBL after 24 m of growing
36 over a cooled aluminium plate, while Ogawa et al. (1985) obtained a depth
37 of only about 20 cm after 12 m on a wind tunnel of similar length. Devices
38 used to artificially thicken the BL include bidimensional blocks or fences, but
39 methods like the ones described by Counihan (1969) and Irwin (1981) for neutral
40 boundary layers (NBLs) give a better control of the BL thickness and turbulence
41 characteristics. The first consists of a castellated barrier wall coupled with a set
42 of quarter-elliptic vorticity generators, while the second makes use of triangular
43 spires, easier to manufacture. Both are normally associated with roughness
44 elements over the floor chosen to provide an aerodynamic rough surface with the
45 desired flow characteristics. Despite being normal practice in NBL simulations,
46 these methods have been rarely used for non-neutral BLs. Robins et al. (2001)
47 employed Counihan’s method for the generation of a thick SBL while Hancock
48 et al. (2013), Hancock and Pascheke (2014), Hancock and Hayden (2016) and
49 Hancock and Hayden (2018) used Irwin’s spires to develop CBLs and SBLs
50 suitable for low-roughness offshore BL conditions. In the latter two papers, in
51 particular, a method to simulate artificially thickened SBLs was deployed, at
52 least for weak to moderate stability levels and no overlying inversion.

53 The effect of roughness in a SBL was studied in the wind tunnel by Williams
54 et al. (2017) and Ohya (2001), who compared his results with the smooth surface
55 simulations by Ohya et al. (1997). Both concluded that turbulence characteris-
56 tics remain substantially similar, with small differences attributed by the former
57 to changes in local stratification. In their work different levels of stability were
58 considered, ranging from weak to very stable. The transition between weak and
59 strong stability conditions were found by Ohya (Ohya et al., 1997; Ohya, 2001)

to happen at a value of the bulk Richardson number equal to 0.25 for both smooth and rough surfaces, while Williams et al. (2017) reported two different values, both of them lower than Ohya’s results (0.10 for the smooth surface and 0.15 for the rough one) with turbulence stress scaling with wall shear only before the transition.

As far as CBL simulations are concerned, Fedorovich et al. (1996) and Fedorovich and Kaiser (1998) carried out wind tunnel experiments, finding roughness and wind shear to be responsible of modifications in the regime of turbulence production, with an increment of the velocity variances closer to the surface respect to the shear-free case for values of the surface shear-to-buoyancy production ratio u_*/w_* greater than 0.3.

The present work aims to investigate techniques for the development of thick high-roughness SBLs and CBLs suitable for studying flow and dispersion in urban areas. For this purpose the method presented by Hancock and Hayden (2018) for SBLs has been applied with success to a higher roughness case. Artificially thickened CBLs have also been investigated. In this case great efforts were put on the enhancement of longitudinal and lateral uniformity of the temperature and velocity fields. In particular, the use of different inlet temperature gradients as well as an overlying inversion have been tested for this purpose.

2. Methodology

2.1. Experimental setup

Flow measurements were performed in the suck-down open-return EnFlo meteorological wind tunnel with a test section 20 m long, 3.5 m wide and 1.5 m high. The x -axis was in the streamwise direction, measured from the working-section inlet; the y -axis was in the spanwise direction, measured from the wind tunnel centre line; the z -axis represented the vertical, starting from the floor. The wind tunnel flow speed could range from 0.3 to 2.5 m/s as measured by a sonic anemometer placed at $x = 5$ m, $y = 1$ m, $z = 1$ m (which provided a reference velocity U_{REF}).

89 The wind tunnel was specifically designed to generate thermally stratified
 90 flows: a series of 15 vertically piled electrical heaters at the inlet section allowed
 91 the generation of a vertical temperature gradient, which combined with the heat-
 92 ing/cooling floor system created the different types of atmospheric stability. For
 93 stable stratification the central 3 m of the floor along most of the working section
 94 in the streamwise direction were cooled by means of recirculating water at the
 95 desired temperature. When CBLs had to be simulated, electrical heater mats
 96 were added on the wind tunnel floor (on top of additional insulating panels).
 97 Their maximum power was 2.0 kW/m^2 , with dimensions $1295 \times 333 \times 5 \text{ mm}$; dif-
 98 ferent arrangements were considered in order to improve the lateral uniformity
 99 (further explanation will be given in the following sections). Panel temperatures
 100 were controlled in a closed-loop system. The air leaving the wind tunnel was
 101 cooled by means of recirculating water in order to keep the laboratory tempera-
 102 ture as constant as possible. The latter presented a vertical variation up to 1°C
 103 between floor and ceiling. Such a gradient was mitigated using a series of fans
 104 that helped air mixing, improving the temperature homogeneity at the inlet.

105 As the main purpose of the work is the development of stratified BLs suitable
 106 for urban studies (for which the micro-scale was of interest), a wind-tunnel scale
 107 of 1:200 was considered for all the cases. In order to obtain sufficiently thick BLs,
 108 Irwin-like spires (Irwin, 1981) after the inlet section and rectangular-shaped
 109 roughness elements on the floor were employed to artificially develop the flow.
 110 For the CBL simulation five spires 1260 mm high, 170 mm wide at the base and
 111 spaced laterally 630 mm were used (shown in Fig. 1). They had been extensively
 112 employed in previous works for generating urban neutrally stratified BLs about
 113 1 m thick (δ), together with surface roughness elements 80 mm wide, 20 mm
 114 high and 2 mm thick placed on the floor in a staggered arrangement with both
 115 streamwise and lateral pitches of 240 mm. For the stable stratification case a
 116 shallower BL was required for scaling issues: in the real atmosphere a SBL tends
 117 to be shallower than a NBL or a CBL. Moreover, a shallower BL would allow us
 118 to move the measurement traverse to locations outside the BL (the measuring
 119 traverse system is currently limited to a maximum height of about 1 m). For this

Figure 1: Wind tunnel and measuring setup.

120 purpose seven spires 986 mm high, 121 mm wide at the base, and 4 mm wide at
121 the top, spaced laterally 500 mm, were designed according to Irwin’s procedure
122 (Irwin, 1981). For all the investigated cases the same roughness element type
123 was employed.

124 Mean and fluctuating velocity measurements were performed by a two-
125 component laser-Doppler anemometer (LDA), via a Dantec 27 mm FibreFlow
126 probe. For the fluctuating temperature measurements a calibrated fast-response
127 cold-wire probe was used. It was placed about 4 mm downstream the LDA mea-
128 suring volume to calculate heat fluxes. This value was chosen in order to reduce
129 the blockage effect of the cold-wire on the measured flow velocity without signif-
130 icantly affecting the correlation between velocity and temperature (see Hancock
131 and Hayden, 2018; Heist and Castro, 1998). Indeed, for a mean convection
132 speed of 0.4 m/s (the lowest measured in the dataset) such separation would
133 correspond to a frequency still comparable with the LDA sampling rate. A
134 thermistor was held about 10 mm on the side of the cold-wire to both measure
135 the mean temperature and calibrate the cold-wire itself. The probes were held
136 by a traverse system mounted on rails on the wind tunnel ceiling, which allowed
137 full three-dimensional movements, ranging from about 6 to 16 m along x , -1 to
138 1 m on y and from 0.05 to 1.0 m on z . In order to measure mean temperatures
139 above such a height during the CBL simulation, a second thermistor was placed
140 430 mm above the LDA measuring volume. Moreover, a double thermistor rake
141 made up of two series of 16 sensors each was employed in order to acquire the
142 temperature field in the section (600 mm downstream the LDA measuring vol-
143 ume). It spanned from 50 mm to 1350 mm of height and its acquisition rate
144 was 0.5 Hz. The sampling rate target for the LDA was set to be around 100 Hz,
145 1000 Hz for the cold-wire, but with a low-pass filter at 250 Hz. The sampling
146 time for the measurements was 3 minutes both in the SBL and NBL tests, while
147 it was increased up to 5 minutes for the CBL. In the latter, an even longer period
148 was advised based on the scatter between sets of profiles, but this would have
149 increased the experiments duration too much. Data acquisition was performed
150 with the standard LabView based software system of the laboratory.

151 *2.2. Measurement scaling*

152 According to the Monin-Obukhov theory (Monin and Obukhov, 1954), the
153 ratio

$$\zeta = \frac{z}{L} = -\frac{(g/\Theta_0)\theta_*}{u_*^2/kz} \quad (1)$$

154 is the most appropriate stability parameter for the surface layer (SL), defined
155 as the region in which the fluxes varies less the 10% of their magnitude. The
156 Monin-Obukhov length L is expressed in terms of the friction velocity $u_* =$
157 $\sqrt{-(\overline{uw})_0}$ and scaling temperature $\theta_* = -(\overline{w\theta})_0/u_*$, in which $(\overline{w\theta})_0$ is the
158 surface kinematic vertical heat flux, g is the acceleration of gravity, k is the von
159 Karman constant (assumed here equal to 0.40) and Θ_0 is a reference temperature
160 (here considered as the mean temperature at approximately the aerodynamic
161 roughness length z_0 height). The wind shear and temperature gradient in the
162 surface layer (which are only function of ζ) can then be represented in non-
163 dimensional form as

$$\phi_m(\zeta) = \frac{kz}{u_*} \frac{\partial U}{\partial z}, \quad \phi_h(\zeta) = \frac{kz}{\theta_*} \frac{\partial \Theta}{\partial z} \quad (2)$$

164 in which Θ is the mean potential temperature. Integrating them between z_0
165 and z leads to the well-known logarithmic expression for the mean streamwise
166 velocity and temperature in the surface layer for the general diabatic case

$$U(z) = \frac{u_*}{k} \left[\ln \left(\frac{z'}{z_0} \right) - \psi_m(\zeta) \right] \quad (3)$$

$$\Theta(z) - \Theta_0 = \frac{\theta_*}{k} \left[\ln \left(\frac{z'}{z_{0h}} \right) - \psi_h(\zeta) \right] \quad (4)$$

167 where $z' = z - d$ to include the contribution of the displacement height d , while
168 z_{0h} is the thermal roughness length. For NBL $\psi_m = 0$, while for the diabatic
169 case

$$\psi_{m,h}(\zeta) = \int_{z_0, z_{0h}/L}^{z'/L} [1 - \phi_{m,h}(\zeta)] \frac{d\zeta}{\zeta} \quad (5)$$

170 In the present work, the parametric equations for ϕ_m and ϕ_h for SBL and
 171 CBL are determined by fitting with the experimental profiles for the two non-
 172 dimensional gradients. A reasonable fitting is guaranteed in all the investigated
 173 stability cases by the following relations (Eqs. 6 for the SBL and 7 for CBL):

$$\phi_m = 1 + 8\zeta, \quad \phi_h = 1 + 16\zeta \quad (6)$$

$$\phi_m = (1 - 16\zeta)^{-1/4}, \quad \phi_h = (1 - 16\zeta)^{-1/2} \quad (7)$$

174 which are coherent with the forms obtained from field data and summarised in
 175 Högström (1988). Forms similar to Eqs. 6 have been found to provide a good
 176 fitting also in Hancock and Hayden (2018). Substituted into Eqs. 3 and 4 they
 177 lead to the following relations for SBL

$$U(z) = \frac{u_*}{k} \left[\ln(z'/z_0) + 8 \frac{z' - z_0}{L} \right] \quad (8)$$

$$\Theta(z) - \Theta_0 = \frac{\theta_*}{k} \left[\ln \left(\frac{z'}{z_{0h}} \right) + 16 \frac{z' - z_{0h}}{L} \right] \quad (9)$$

178 and for the CBL

$$U(z) = \frac{u_*}{k} \left[\ln \left(\frac{z'}{z_0} \right) - \ln \left(\frac{(1 + \alpha)^2 (1 + \alpha^2)}{(1 + \alpha_0)^2 (1 + \alpha_0^2)} \right) \right] + 2 \frac{u_*}{k} (\tan^{-1}(\alpha) - \tan^{-1}(\alpha_0)) \quad (10)$$

179 with $\alpha = (1 - 16z'/L)^{1/4}$ and $\alpha_0 = (1 - 16z_0/L)^{1/4}$;

$$\Theta(z) - \Theta_0 = \frac{\theta_*}{k} \left[\ln \left(\frac{\beta - 1}{\beta + 1} \right) - \ln \left(\frac{\beta_0 - 1}{\beta_0 + 1} \right) \right] \quad (11)$$

180 with $\beta = (1 - 16z'/L)^{1/2}$ and $\beta_0 = (1 - 16z_{0h}/L)^{1/2}$.

181

182 The Monin-Obukhov theory also links the value of the gradient Richardson
 183 number ($Ri = g(\partial\Theta/\partial z)/[\Theta_0(\partial U/\partial z)^2]$) to the scaling ratio ζ using

$$Ri(\zeta) = \zeta(\phi_h/\phi_m^2) \quad (12)$$

184 While the bulk Richardson number Ri_b is here calculated as

$$Ri_b = \frac{g(\Theta_\delta - \Theta_0)\delta}{\Theta_0 U_\delta^2} \quad (13)$$

185 where Θ_δ and U_δ are, respectively, the mean temperature and mean streamwise
 186 velocity measured at the BL top δ . About the determination of δ from measured
 187 data in the SBL, Stull (1988) listed a series of criteria which might be used,
 188 highlighting that a unique method still does not exist and different procedures
 189 bring to arbitrary different results. For this reason, in the present study δ was
 190 determine by eye taking into account all the profiles. In particular, $\overline{uw}$ and $\overline{w\theta}$
 191 had to be less than 5% the values at the surface and U had to be at (or very
 192 close to) its free stream value. Differently, for the CBL δ is usually determine as
 193 the height at which $\overline{w\theta}$ experiences a minimum (Stull, 1988). However, in the
 194 present study such condition appeared to happen always above the measuring
 195 range of the traverse, hence a different method was employed. It considered a
 196 fitting of the $\overline{w^2}$ profile with a reference curve (as better detailed in Section 4.2).

197 For the mixed-layer (ML) of the CBL, differently from the SL, the length
 198 scale is considered to be the BL depth δ , while the velocity and temperature
 199 scales are, respectively

$$w_* = \left[\frac{g}{\Theta_0} (\overline{w\theta})_0 \delta \right]^{1/3}, \quad \tilde{\theta} = \frac{(\overline{w\theta})_0}{w_*} \quad (14)$$

200 as summarised by, e.g., Kaimal and Finnigan (1994).

201 2.3. Estimation of surface properties

202 In order to estimate L , the values of $\overline{uw}$ and $\overline{w\theta}$ at the surface have to be
 203 extrapolated from the values in the SL. The same can be said for the profiles
 204 of mean streamwise velocity and temperature, used to estimate the roughness

lengths. However, in an urban boundary layer due to the high level of roughness typically a roughness sub-layer (RSL) develops, in which the measured quantities are not independent from the position relative to local obstacles (here represented by the rectangular roughness elements). The same surface elements shape and arrangement employed here was investigated (among others) by Cheng and Castro (2002) in neutral stratification, for which they found a RSL height equal to $5H$ (where H is the height of the roughness element). Above such layer they identified an inertial sub-layer (ISL), defined after Oke (1987) as the region where the vertical variation of shear stress was less than 10% (also called constant flux layer), that extended up to $10H$. In their work two methods were investigated to estimate u_* and z_0 : the first attempted to use only the points in the ISL where the measured values are expected to be independent from the position, while the second method included also the points in the RSL, but spatially averaged among different locations. In order to evaluate the best solution, both the methods were verified here for SBL, NBL and CBL; the results are shown in Fig. 2 for a location about 12 m from the inlet. The black points are the values obtained scanning the region downstream a roughness element with a grid of 20 measuring locations (as shown in the map at the bottom of the figure), repeated for 4 heights ($2.5H$, $5H$, $7.5H$, $10H$).

For the SBL (a-d in the figure) the data acquired at $2.5H$ shows a clear dependence from the roughness, effect which is widely reduced at $5H$, suggesting a similar height for the RSL. However, a constant-flux layer is not clearly identifiable in the region above (the same can be said for the NBL). On this aspect, Cheng et al. (2007) pointed out that a genuine constant-flux layer may not be expected in a wind tunnel with a non-zero pressure gradient as it is the one used here. Despite this, the mean values of $\overline{uw}$ and $\overline{w\theta}$ for each height (red circles in Fig. 2c and d), that are representative of the spatial averaged profile, show a fairly linear trend above $5H$, which extends down to the floor. This result suggests that a linear fitting in the region above the RSL may be in this case a suitable method to estimate the shear stress and heat flux values at the surface. Such result is confirmed by the analysis of the vertical profiles, one of

236 which is reported in the figure (blue squares), which also shows that the linear-
 237 ity extends considerably above $10H$. For the mean velocity and temperature
 238 the variability in the RSL is lower, and both the methods brought generally to
 239 a similar solution, having the care to not consider the lower points in case they
 240 are too far from the trend of the above region. Similar results were obtained for
 241 the NBL (not shown) but with more variability due to the larger turbulence.

242 For the CBL the points present a higher level of scatter, clearly shown by
 243 the two repetitions of the same vertical profile in Fig. 2e-h. The scatter of the
 244 measurement makes less evident the local effect of the roughness. Nevertheless,
 245 the shear stress profile exhibits an approximately constant flux region which
 246 extends from the bottom up to about $25H$. A similar trend is shown by the heat
 247 flux, but in this case accompanied by a slight reduction below $5H$. Despite such
 248 difference, from the analysis of all the vertical profiles, the most robust method
 249 to estimate both $(\overline{uw})_0$ and $(\overline{w\theta})_0$ appeared to be including all the points of the
 250 constant flux region. Finally, for the mean temperature and velocity profiles in
 251 the CBL, similar considerations to those for the SBL can be made.

252 In the following, all the presented parameters are calculated from the average
 253 of at least three vertical profiles measured at the centre line and at a distance
 254 from the inlet of 12.5, 14 and 15.5 m, in order to have a streamwise average in
 255 the region where the boundary layer is reasonably more developed. For part of
 256 the CBL data, each profile was also repeated twice to reduce the scatter (only
 257 the average of the two repetitions will be shown in the following graphs).

258 **3. Stable boundary layer**

259 In this section we firstly discuss about the effects of the main temperature
 260 control parameters. Then, we investigate the repeatability of the same stratifi-
 261 cation at different Reynolds numbers. Finally, we analyse SBLs with moderate
 262 stability in more details by comparing the results with data obtained in a NBL,
 263 with lower roughness and in field measurements.

Figure 2: Roughness element scan for $Ri_b = 10$ (a-d) and -0.5 (e-h). The scan positions are reported in the scheme at the bottom.

3.1. Temperature controls

The three main parameters to be set in order to simulate a SBL in the EnFlo wind tunnel are the maximum temperature difference $\Delta\Theta_{\text{MAX}}$ between cooled floor Θ_0 and free stream flow Θ_∞ , the length of uncooled floor between the inlet and cooled part, and the imposed temperature profile at the inlet section up to the BL height. A fourth temperature parameter would be the gradient of temperature imposed above the BL, if an overlying inversion were considered. However only zero-strength overlying inversion cases were analysed here in order to reduce the number of parameters.

In the present study, different values for $\Delta\Theta_{\text{MAX}}$ were employed, ranging from 6 to 16°C. The desired Ri_b was also obtained modifying the flow velocity and so allowing the air to be cooled by the floor for a different amount of time.

The second parameter to be considered is the length of uncooled floor after the inlet. Previous studies conducted in the EnFlo laboratory for offshore BLs (Hancock and Hayden, 2018) found a dependency of the shear stress $\overline{uw}$ profile from this parameter. Investigating different uncooled floor lengths, the best result in terms of longitudinal uniformity among different locations was found with 5 m for both the offshore BL and the high-roughness case presented here. More in general, the length of uncooled floor has to be chosen accordingly to the inlet temperature profile.

Finally, a proper inlet temperature gradient has to be considered. The easiest solution would be to impose a uniform inlet temperature and allow the stability to grow thanks to the cooling effect of the floor. However, Hancock and Hayden (2018) found that with this configuration the upper part of the layer remained unaffected by the non-neutral stratification, with a mean temperature constant with height, while temperature fluctuation and heat fluxes approached zero at lower heights than the Reynolds shear stress. This behaviour was likely caused by the advection downstream of the uniform temperature at the inlet (increased by the reduced level of turbulence). On the other hand, also a near constant inlet temperature gradient does not seem to be the best choice. This option was investigated by Ohya and Uchida (2003) and Hancock and Pascheke

Figure 3: Effect of variation of inlet temperature profile gradient (a) on mean (b) and fluctuating (c) temperature profiles at $x = 6480$ mm. $U_{REF} = 1.50$ m/s and $\Delta\Theta_{MAX} = 16^\circ\text{C}$

(2014) and the resulting BL presented decreasing temperature fluctuations with height z , followed by a rise in the middle region which was attributed by the authors to a too large gradient of mean temperature in the same region. More promising is the approach experimented by Hancock and Hayden (2018). The idea was to impose the measured profile in a naturally-growing SBL (where “naturally-growing” is referred to a BL created just by friction with the cooled floor, without any flow generator or roughness element) as inlet temperature profile, starting from an initial uniform profile. The acquired temperature profile was stretched to fit the desired $\Delta\Theta_{MAX}$ and BL height δ and applied to the inlet section with flow generators and roughness elements in place again. The resulting profile is shown in Fig. 3a and hence referred to as “Natural”.

However, a direct application of such an initial condition (not shown here) created an undesired large peak in the middle region of the temperature fluctuation graph. Therefore, the original gradient was reduced applying corrective

309 factors until the best solution was found. The other cases in Fig. 3 represent
 310 respectively a reduction of a factor 2/5, 3/10, 1/5 of the “natural” one; the
 311 uniform temperature case is also shown. They were acquired after just 1.5 m
 312 of floor cooling, and so still in the “developing region” of the flow. The most
 313 significant effect of varying the inlet gradient is on the temperature fluctuation;
 314 in fact, even though the temperature standard deviation profiles show the same
 315 trend in the bottom part (Fig. 3c) a peak is present in the middle region for
 316 the 2/5 case (and it would be even worse approaching the “natural” gradient).
 317 The peak is quite reduced for the 3/10 case and disappears for the 1/5 and
 318 the uniform profile. However, as compromise, the 3/10-reduced version of the
 319 inlet temperature profile was chosen as upstream condition for the following
 320 experiments.

321 *3.2. Reproducibility of stratification at different Reynolds numbers*

322 The wind velocity is normally not a critical parameter when simulating
 323 NBLs: with only a lower value limitation dictated by the requirement of Reynolds
 324 number independence, the range of usable velocities is mostly limited by the
 325 wind tunnel capabilities. On the other hand, when simulating thermally strati-
 326 fied BLs any small change in velocity produces a large effect on the stratification,
 327 being $Ri_b \propto U^{-2}$. Lower velocity values become desirable, in particular, when
 328 larger Ri_b are requested, but the temperature difference parameter must be kept
 329 within a certain limit.

330 The purpose here is to investigate the similitude of artificially thickened
 331 SBLs obtained from different velocities but matching the same Ri_b by means
 332 of adjusting $\Delta\Theta_{\text{MAX}}$ accordingly. The reference velocity (U_{REF}) was set to 1.0,
 333 1.25 and 1.5 m/s, correspondent to $Re_\delta = U_\delta\delta/\nu$ (with ν air kinematic viscosity
 334 at Θ_0) from 6.1×10^4 to 9.2×10^4 . The stratification level was kept nominally
 335 constant by adjusting the $\Delta\Theta_{\text{MAX}}$ at the inlet (as shown in Table 1) in order
 336 to match a Ri_b of 0.14 in all three cases.

337 Fig. 4 shows the non-dimensional vertical profiles of mean streamwise ve-
 338 locity, Reynolds shear stress, mean temperature, vertical kinematic heat flux,

Table 1: Main scale parameters for $Ri_b = 0.14$ case obtained with different Re_δ

$Re_\delta (\times 10^4)$	9.2	7.7	6.1
U_{REF} (m/s)	1.50	1.25	1.00
$\Delta\Theta_{\text{MAX}}$ ($^\circ\text{C}$)	16.0	10.8	6.4
u_*/U_{REF}	0.053	0.053	0.053
z_0 (mm)	2.4	2.3	2.3
z_{0h} (mm)	0.021	0.007	0.013
θ_* (K)	0.35	0.24	0.16
δ/L	0.64	0.63	0.65
Ri_b	0.14	0.14	0.14

339 gradient Richardson number, Brunt-Väisälä frequency (calculated as $N_{BV} =$
 340 $\sqrt{(g/\Theta)(\partial\Theta/\partial z)}$), streamwise and vertical velocity length scales. The latter
 341 were computed from the numerical integration of the autocorrelation coefficient,
 342 assuming the Taylor’s hypothesis of “frozen turbulence”. All the graphs
 343 indicate a fairly good agreement among the profiles of the three BLs. Also
 344 the values of δ/L in Table 1 appear to scale very well (with $\delta \approx 850$ mm for
 345 all three cases), confirming that the stratification remained unchanged. To be
 346 noted that, even though in Fig. 4 only one profile at $x = 12.5$ m for each case
 347 is shown, the values in the table were estimated from the average of profiles at
 348 three different locations (as explained in paragraph 2.3).

349 The aerodynamic and thermal roughness lengths were estimated with a non-
 350 linear least-squares fitting of Eq. 8 and 9 with the profiles of mean velocity and
 351 temperature, respectively. The displacement height was set equal to zero (here
 352 and for all the cases analysed) as indicated also by Cheng and Castro (2002) for
 353 the same roughness. Letting it varying freely led in some cases to inconsistent
 354 values without an effective improvement of the fit. The obtained values, despite
 355 being the result of different approximations and dependent by the methodology
 356 chosen so far, are consistent each other, since they do not differ too much in
 357 the three BLs. The Ri profile for the three cases coincides quite well with
 358 Eq. 12 for the same height for which the fitting is verified between the log-

Figure 4: Profiles of mean streamwise velocity, Reynolds shear stress, mean temperature, vertical kinematic heat flux, gradient Richardson number, Brunt-Väisälä frequency, stream-wise and vertical velocity integral lengthscales for different Reynolds numbers but same bulk Richardson number ($Ri_b = 0.14$). Black lines are, respectively, (a) Eq. 8, (c) Eq. 9, (e) Eq. 12, while (g) and (h) are from Kaimal (1973)

Figure 5: Power spectral density of streamwise velocity for different Reynolds numbers but same bulk Richardson number ($Ri_b = 0.14$). $z = 190$ mm. Black line is $-2/3$ slope reference.

law and the velocity profile. For the integral length scales in Fig. 4g and h a comparison with field data is provided as well, by means of the empirical relations $\Lambda_U = 0.082z/Ri$ and $\Lambda_W = 0.015z/Ri$ from Kaimal (1973) (in which Ri was calculated using Eq. 12).

Finally, Fig. 5 shows the power spectral density graph of streamwise velocity for the three cases considered here against the non-dimensional frequency $n = fz/U$ (where f is the dimensional one). The maximum peak frequency and the general shape is similar for all cases, while the slower case exhibits a steeper reduction at the higher frequencies of the inertial sub-range, also compared to the $-2/3$ reference line. This behaviour is expected and compatible with a reduction of the Reynolds number. Difference that, however, does not preclude the similitude of mean and turbulent quantities already commented.

The conclusion drawn from this data is the confirmation that for an artificially thickened BL, the same level of stability (in terms of ratio δ/L and similitude of non-dimensional mean and turbulent profiles) can be obtained for different velocities by matching the Ri_b . Moreover, the reduction in Re does not seem to affect mean and turbulent quantities. This result is also supported by the fact that the roughness Reynolds number $Re_* = u_* z_0/\nu$ (used to evaluate whether the surface is fully rough) is for the slowest case still greater than 8, and thus larger than the minimum limit of 1 indicated by Snyder and Castro

379 (2002) for sharp-edged roughness elements in a NBL.

380 3.3. Comparison with NBL, different stratifications and surface roughness

381 In this section a SBL characterised by $Ri_b = 0.21$ (obtained imposing $\Delta\Theta_{\text{MAX}}$
382 $= 16^\circ\text{C}$ and $U_{\text{REF}} = 1.25 \text{ m/s}$) is compared with a NBL developing from the
383 same spires.

384 Fig. 6 shows the stable (S) profiles at three streamwise locations compared
385 with a neutral (N) one, for which (for clarity) only the average profile at the
386 same three locations is plotted. For the latter, the measured points differ from
387 the average profile less than $\pm 0.5\%$ on U mean and less than $\pm 5\%$ for the other
388 quantities shown (except for the vertical length scale which differs up to 18%).

389 In Fig. 6 the mean velocity reaches a maximum and the Reynolds shear stress
390 profile approaches zero for approximately $z = 850 \text{ mm}$, which suggests a δ value
391 of the same amount (equivalent in full-scale to a BL 170 m deep). Such a value
392 is equal for stable and neutral stratifications. This allows to speculate that the
393 combination of chosen spires and inlet temperature profile overcomes the effect
394 of stability to reduce δ . Also the general shape of the mean velocity profile is
395 fairly similar between the two stratifications, but with the SBL characterised, as
396 expected, by lower velocities at the bottom and higher at the top compared to
397 the NBL. The aerodynamic roughness length is also almost the same between
398 the two cases ($z_0 = 2.3 \text{ mm}$ for SBL and 2.2 for NBL). The small effect of
399 the stratification on the mean velocity profile leads to the conclusion that such
400 profile is mostly controlled by the spires (as also observed in Hancock and
401 Hayden, 2018).

402 The reduction of turbulence due to stratification involves the entire BL and
403 it is evident for the variances and the covariance of the velocity which appear
404 up to 50% smaller. Same reduction is also experienced by the integral length
405 scales, while the u_* is about 30% lower (from $u_*/U_{\text{REF}} = 0.065$ to 0.047).

406 Fig. 7 presents a comparison between non-dimensional profiles of the two
407 stable and one neutral BLs already introduced plus a more stable one obtained
408 with the same $\Delta\Theta_{\text{MAX}} = 16^\circ\text{C}$ but reducing the velocity to $U_{\text{REF}} = 1.0 \text{ m/s}$.

Figure 6: Profiles of mean streamwise velocity, Reynolds shear stresses and integral length scales for a SBL with $Ri_b = 0.21$ and the reference NBL. The NBL profile is obtained as average of the ones acquired at the same three locations of the SBL.

Figure 7: Profiles of non-dimensionalised streamwise and vertical velocity variance, Reynolds shear stress, temperature variance, streamwise and vertical kinematic heat flux for different level of stability and roughness. Black points are field data from Caughey et al. (1979)

Table 2: Main scale parameters for reference neutral and three different stability cases obtained with different velocities, plus one lower roughness case

Ri_b	0	0.14	0.21	0.33	0.21 (LR)
U_{REF} (m/s)	1.25	1.50	1.25	1.00	1.25
$\Delta\Theta_{\text{MAX}}$ ($^{\circ}\text{C}$)	0	16	16	16	16
u_*/U_{REF}	0.065	0.053	0.047	0.040	0.042
z_0 (mm)	2.2	2.4	2.3	2.4	0.6
θ_* (K)	-	0.35	0.34	0.30	0.30
δ/L	0	0.64	1.13	2.18	1.27

A fifth case is also added, generated with the same settings of the third, but with a reduced roughness density (in the case the roughness elements rows were 720 mm apart) and characterised by a z_0 four times smaller. The main parameters of the five cases are summarised in Table 2. All the profiles shown are the result of averaging from three different locations (as for the NBL in Fig. 6). The longitudinal variability of the profiles ranges from a minimum of $\pm 2\%$ for the temperature variance at Ri_b 0.14 to $\pm 15\%$ for the covariances when Ri_b 0.33 (with the majority of the profiles below 10%). In general, the variability increased with Ri_b . Moreover, in the lower-roughness case this variability was found to be larger than the higher-roughness case with similar stability.

Among the three high-roughness stable cases, the largest differences in turbulent properties appear in the lower half of the BL. This behaviour is explainable by the fact that the cooling time is increased with a reduced velocity. This causes a larger reduction of turbulence in the bottom part, but the reduced vertical displacement due to the stratification prevents the modification farther away from the floor. This behaviour makes the Reynolds shear stress of the stable cases deviate from the almost-linear trend of the reference NBL. In the bottom half of the BL, the lower roughness case is much more similar to the $Ri_b = 0.33$ case with high roughness than to the high-roughness case with the same Richardson number ($Ri_b = 0.21$). This trend is particularly evident in the $\overline{uw}$ graph. The results suggest that a reduction of the roughness has the

430 same effect on the turbulence profiles of an increment of the stratification, at
 431 least in the bottom part of the BL. The upper part, on the contrary, seems to
 432 be less influenced by the roughness and the inlet conditions are predominant in
 433 shaping the profiles.

434 Despite the modifications described, all the profiles scale reasonably well
 435 with the surface shear stress. This is in contrast with what shown, e.g., by
 436 Ohya (2001), where for $Ri_b > 0.25$ the turbulence profiles were expected to
 437 collapse in the very stable regime. As mentioned in the introduction, Williams
 438 et al. (2017) indicated an even lower threshold ($Ri_b > 0.15$) for the rough
 439 surface case. A possible explanation of this discrepancy is that the method
 440 employed to artificially thicken the BL, being originally developed for NBL,
 441 may not be suitable for very SBLs and further work would be necessary to
 442 come to a conclusion. On the other hand, Williams et al. (2017) also pointed
 443 out that the Ri_b could be a too crude indication to determine the transition in
 444 the stability regime. They quoted Flores and Riley (2011), claiming that the
 445 Reynolds number based on L and u_* ($Re_L = Lu_*/\nu$) could possibly be a better
 446 indicator of the transition, found to happen for values of Re_L lower than 100-
 447 130, independently from the surface roughness. For all the presented cases Re_L
 448 was greater than 1000, so a very stable regime based on this criterion should
 449 not be expected. In Fig. 7 the field data measurements from Caughey et al.
 450 (1979) are reported as well. The agreement is reasonably good, in particular for
 451 the $Ri_b = 0.14$ case.

452 The final comments are on the lateral uniformity and standard error ex-
 453 perience with stable stratification and reference NBL. The former, looking at
 454 lateral profiles performed at a height of 300 mm spanning a length of ± 1000 mm
 455 from the centreline, was found to be generally quite good, with a mean velocity
 456 variation of the order of $\pm 2\%$, less than 1 for the mean temperature, around 5%
 457 for the variances and 10% for the covariances. Similar values were obtained for
 458 the NBL.

459 The standard error on mean U and Θ was less than $\pm 1\%$, around 5% for
 460 the variances and 15% for the covariances. To be noted that the lateral (as well

as the longitudinal) variability are of the order of the standard error. Similar quantities were found for the reference NBL. The standard error in the SBL was around $\pm 1\%$ for mean velocity, 5% for the variances and 10% for the covariances. For the NBL, similar values were obtained, except the streamwise velocity variance for which the standard error was closer to 10%.

4. Convective boundary layer

Similarly to the SBL, in order to simulate a CBL the temperature difference $\Delta\Theta_{\text{MAX}}$ and the flow velocity are the main ways to control the (unstable) stratification strength. The inlet temperature profile and the strength of the inversion layer imposed above the BL are other important parameters to consider, in particular as they were found to somewhat influence the lateral uniformity of the flow and temperature fields. Before considering the effect of this inlet temperature controls some considerations on the floor heater mats must be discussed. As already mentioned, the laboratory employs 2950 mm long rectangular heater panels, so that when placing them transversally on the floor, the last 275 mm on both sides are not heated (being the test section 3500 mm wide). In the past, Perspex panels were placed within the test section to reduce its width, but this remedy was not pursued in this case because the entire wind tunnel width was necessary for future experiments with the urban model. Therefore four different heater mats arrangements were considered, the first of which consisted in adjacent panels placed transversally, with 275 mm on both sides unheated. In Fig. 8 a lateral profile of temperature acquired with the double thermistor rake shows a reduction of up to 4% respect to the centre line (2% in the region ± 1 m). In the other configurations longitudinal panels were added on the sides in order to cover a wider region of the floor¹. The graph shows that the configuration in which the largest part of the test section is heated does not present the best uni-

¹In configuration 2 the longitudinal panel temperature was increased respect to the transversal one until the best uniformity was achieved. In Configurations 3 and 4 all the panels were set at the same temperature

487 formity, with hot spots closer to the walls, while a reasonable compromise is the
 488 third configuration in which 110 mm are left unheated (without the complexity
 489 of adjusting the longitudinal panels temperature as for configuration 2).

490 *4.1. Temperature controls*

491 For the CBL an inlet temperature gradient and a capping inversion layer were
 492 considered separately. Differently from the SBL, using a NBL as starting point
 493 (uniform inlet temperature profile) and obtaining a CBL only by means of the
 494 heated floor was found acceptable. This approach was employed, for instance,
 495 by Fedorovich and Kaiser (1998) and Ohya and Uchida (2004). Differently,
 496 Hancock et al. (2013) suggested to adopt as inlet setting the temperature profile
 497 measured in a section downstream (starting from a uniform inlet profile) and
 498 iterating until a matching of the shape between the two was achieved. This
 499 method was tested in the present study with high-roughness conditions with
 500 the purpose of enhancing the longitudinal uniformity and reducing the fetch
 501 necessary to obtain a sufficiently developed CBL. However, the improvements
 502 were generally difficult to appreciate and hard to separate from the experimental
 503 scatter. Moreover, applying a negative inlet gradient was found to worsen the
 504 lateral uniformity (at least in the present case). Fig. 9 shows the lateral profiles
 505 of Reynolds shear stress, temperature variance and mean streamwise velocity
 506 for different inlet gradients. Three cases were considered: uniform temperature,
 507 “full gradient” from the direct application of the method and half gradient. The
 508 turbulence is less laterally uniform in the “full gradient” case in both graphs.
 509 While the Reynolds shear stress graph shows comparable results for the half
 510 gradient and uniform cases, the latter presents a slightly better uniformity in
 511 the central region of the temperature variance plot. Interestingly, the non-
 512 uniformity due to the gradient affects only turbulent quantities and heat fluxes,
 513 while mean velocity (Fig. 9d) and temperature profiles (not shown) seem not to
 514 be affected.

515 A capping inversion is a characteristic part of the CBL. Some previous stud-
 516 ies (Ohya and Uchida, 2004; Fedorovich and Kaiser, 1998) paid great attention

Figure 8: Comparison between different floor heater mats arrangements, whose plan-view is also represented ($x = 14000$ mm, $z = 300$ mm, $U_{\text{REF}} = 1.25$ m/s, $\Delta\Theta_{\text{MAX}} \approx 20^\circ\text{C}$). Θ_c is the temperature in the centreline

Figure 9: (a) Vertical profile of inlet temperature. Lateral profiles of Reynolds shear stress (b), temperature variance (c) and mean streamwise velocity (d) at $z = 300$ mm ($U_{REF} = 1.0$ m/s, $\Theta_0 = 60^{\circ}C$, $x = 13900$ mm, floor configuration 4)

Figure 10: (a) Vertical profile of inlet temperature with different inversion strength. (b) Lateral profiles of temperature acquired with thermistor rake at $z = 1225$ mm. ($U_{REF} = 1.0$ m/s, $\Theta_0 = 60^\circ\text{C}$, $x = 14500$ mm)

to the inversion layer and the entrainment. In the present study the focus is mainly on the simulation of the lower part of the CBL, which is most relevant for flow and dispersion studies in the urban environment. For this reason the correct representation of a capping inversion was not deemed essential. Weak linear inversions were applied above 1 m from the inlet and with a maximum gradient of $30^\circ\text{C}/\text{m}$. Inside this range no effects were experienced in the bottom half of the BL. However, a proper calibrated inversion capping the BL was found to greatly enhance the lateral uniformity. In Fig. 10 the lateral profile of temperature in the upper part with no inversion is compared with two cases with inversions (respectively with a $10^\circ\text{C}/\text{m}$ and $20^\circ\text{C}/\text{m}$ temperature increase). The lateral temperature profile appears colder in the central region compared to the sides. The opposite was found for the $20^\circ\text{C}/\text{m}$ inversion. On the other hand, employing the $10^\circ\text{C}/\text{m}$ inversion resulted in a better lateral uniformity of the temperature profiles. This fact seems to suggest that a proper inversion can be defined to match the temperature on the sides with the temperature in the central region. The beneficial effect of such an increased-temperature uniformity can be observed, for example, by comparing the vertical profiles of streamwise mean velocity in the centreline with the ones in the sides (Fig. 11).

The length of unheated floor after the inlet did not affect the CBL as it was noted in the SBL case. Only 1 and 4 m were tested and no significant

Figure 11: Mean velocity profiles with (a) no inversion and (b) inversion 10°C/m at $x = 13900$ mm. ($U_{REF} = 1.0$ m/s, $\Theta_0 = 60^\circ\text{C}$)

improvements were observed by delaying the heating, apart from an undesired reduction of the level of instability. 1 m was the length used for all the results shown.

4.2. Mean and turbulent profiles

The strongest CBL case experimented here, obtained with uniform inlet temperature and an inversion of about 10°C/m (adjusted to enhance the lateral uniformity), is presented in Fig. 12 and compared with a reference NBL. The longitudinal variability for the latter is comparable with the already presented NBL (obtained with the smaller spires). The main scale parameters are reported in Table 3.

The streamwise mean velocity profile is greatly modified by the stratification: Eq. 10 readily fits with the bottom region, up to a sharp “knee” at $z \approx 150$ mm, while the region above shows constant velocity, compatible with the trend expected in a mixed-layer. The velocity profile presented in Fig. 2e, being a less unstable case ($Ri_b = -0.5$ instead of -1.5), had a shape more similar to the NBL. The aerodynamic roughness length does not seem to be affected by the different stratification (being 2.0 mm for both CBL and NBL), while z_{0h} has a value similar to the SBLs previously presented. The mean temperature also follows the similarity in the SL while the inversion appears notably reduced from the value imposed at the inlet, mostly due to mixing from below. Reynolds stresses have

Figure 12: Profiles of mean velocity, Reynolds shear stresses, mean temperature and vertical kinematic heat flux for a CBL case ($Ri_b = -1.5$) and a reference neutral at the centreline. The NBL profile is obtained as average of the ones acquired at the same three locations of the CBL. Black lines in (a) and (e) are Eqs. 10 and 11, respectively; blue line in (c) is Eq. 15; black line with dots in (e) is the inlet temperature profile.

Table 3: Main scale parameters for two different unstable cases obtained with different velocities and temperature settings, plus reference neutral. ($\Delta\Theta_{\text{MAX}}$ is indicated without considering the temperature inversion)

	N	HR2	HR1(U)
U_{REF} (m/s)	2.0	1.25	1.0
$\Delta\Theta_{\text{MAX}}$ ($^{\circ}\text{C}$)	0	-23	-36
δ (m)	1.0	1.2	1.3
u_*/U_{REF}	0.065	0.084	0.100
z_0 (mm)	2.0	1.8	2.0
θ_* (K)	-	-0.78	-1.4
$\tilde{\theta}_*$ (K)	-	0.56	0.79
u_*/w_*	-	0.72	0.56
δ/L	0	-1.1	-2.2
Ri_b	0	-0.5	-1.5
Re_δ ($\times 10^4$)	13.3	8.7	6.9

557 much larger values compared to the neutral case (u_*/U_{REF} is here 0.10 against
 558 0.067). $\overline{uw}$ and $\overline{w\theta}$ have a similar trend, as already found for the $Ri_b = -0.5$
 559 case in Fig. 2, but the region of constant flux values extend now higher. The
 560 shape of the $\overline{w^2}$ profile is significantly different, showing an expected rise with z
 561 followed by a decrease, instead of a monotonic reduction. Canonical similarity
 562 functions (see, e.g., Kaimal and Finnigan, 1994) do not seem to apply for this
 563 case, characterised by a low value of $\delta/|L|$ (≈ 2.2). Moreover, the ratio between
 564 friction velocity and convection velocity scale u_*/w_* is here equal to 0.55 and,
 565 as reviewed by Fedorovich et al. (2001), when such ratio is larger than ≈ 0.35
 566 longitudinal rolls due to shear start to form, causing turbulence statistics to de-
 567 viate from the free-convection case. Hancock et al. (2013) proposed a modified
 568 version to take into account the effect of the shear also in the ML. Here their
 569 relation for $\overline{w^2}$ in the ML is reported.

$$\frac{\overline{w^2}}{u_*^2} = 6.63 \left(1 + 0.8 \frac{\delta}{|L|} \right)^{2/3} \left(\frac{z}{\delta} \right)^{2/3} \left(1 - 0.8 \frac{z}{\delta} \right)^2 \quad (15)$$

Eq. 15, in particular, is used here to estimate the BL depth δ by fitting with the $\overline{w^2}$ profile (Fig. 12b): the value of 1.3 m provides a reasonable fitting. To be noted that at the chosen geometric ratio of 1:200 such height would correspond to 260 m on full-scale, which is quite small compared to normal CBL depths. Such a limitation, dictated by the dimensions of the wind-tunnel, is not deemed critical in this case as the models have, normally, considerably smaller dimensions at the urban micro-scale of interest.

Fig. 13 shows the non-dimensional Reynolds stresses, temperature fluctuation and vertical heat flux. The high-roughness case previously presented (here called HR1) is compared with the one characterised by the same roughness but weaker instability (HR2). The longitudinal variability for the plotted quantities was below $\pm 10\%$, and for the variance of the velocity components for case HR1 was less than $\pm 2\%$, four times lower than case HR2, suggesting that the increment in the mixing given by a larger Ri_b is beneficial for the longitudinal uniformity. The case U5 from Hancock et al. (2013) is also plotted and allows a comparison with a low-roughness case with similar instability (in this run $h/L \approx 1.26$ and $u_*/U_{\text{REF}} = 0.055$). The case E2 from Ohya and Uchida (2004) is reported as well (characterised by $h/L = 3.11$). The $\overline{u^2}$ graph shows a good agreement between case HR2 and U5, with similar instability but different roughness. The same can be said for the $\overline{w^2}$ profiles. Again for $\overline{u^2}/w_*^2$ case HR1 presents lower values compared with the weaker case HR2. As far as non-dimensional temperature variance and vertical heat flux are concerned, a good agreement is shown between all the presented experimental cases. The resemblance with the data from Ohya and Uchida (2004) is particularly significant, since no spires were used in their experiments.

Comparison with field measurements is provided by means of Caughey and Palmer (1979), Wilczak and Phillips (1986) and Wood et al. (2010). The non-dimensional streamwise velocity variance experiences a degree of variability among the different authors comparable with the one found experimentally. For the vertical velocity variance the best agreement is found with Wilczak and Phillips (1986), while Caughey and Palmer (1979) and Wood et al. (2010) report

Figure 13: Profiles of non-dimensional Reynolds stresses, temperature variance and vertical kinematic heat flux. Data is compared with Hancock et al. (2013) (case U5), Caughey and Palmer (1979), Ohya and Uchida (2004) (case E2), Wilczak and Phillips (1986) and Wood et al. (2010)

601 lower values (the opposite for the temperature variance). Finally, the vertical
602 heat flux differs from the canonical linear trend found in field data. However,
603 the result is close to what found by Ohya and Uchida (2004) for similar insta-
604 bility. To be noted that for stronger instability cases Ohya and Uchida (2004)
605 obtained profiles of $\overline{w\theta}$ closer to the canonical linear.

606

607 As for the SBL the final comment is on the lateral uniformity and standard
608 error. The spanwise variation of mean quantities was about $\pm 1\%$, around 10%
609 for the variances and 15 for the covariances. For the reference NBL the tur-
610 bulence lateral variation was smaller, around 6% for the variance and 10 for
611 $\overline{uw}$. The standard error on mean U and Θ was about $\pm 1\%$, up to 10% for
612 the variances and up to 18% for the covariances. Finally, the reference NBL
613 experienced values of variability and standard error of about 5% for variances
614 and up to 18% for $\overline{uw}$.

615 5. Conclusion

616 Experiments involving the simulation of stable and convective boundary lay-
617 ers over a very rough surface have been performed in a thermally-stratified wind
618 tunnel. Artificial thickening by means of Irwin’s spires was used to accelerate the
619 formation of a sufficiently deep boundary layer, suitable for urban-like boundary
620 layer flow and dispersion studies.

621 For the stable boundary layer, the methodology presented in Hancock and
622 Hayden (2018) for low-roughness offshore surface conditions has been success-
623 fully applied to cases with higher-roughness. The reproducibility of mean and
624 turbulent profiles at different Reynolds numbers by matching the bulk Richard-
625 son number has been verified. Different levels of stratification produced modi-
626 fications in the turbulence profiles of the lower half of the BL, but little or no
627 change in the region above. The same can be said for the effect of the sur-
628 face roughness, whose reduction was found to produce results similar to what
629 observed after an increase in the stratification. A case with stronger stability

(in terms of bulk Richardson number greater than 0.25) was simulated but the turbulence profiles continued to scale with the lower stability cases, suggesting that the employed spires may not be suitable to simulate such extreme condition, though further studies are needed. The results were in reasonably good agreement with field measurements (Caughey et al., 1979).

For the simulation of a convective boundary layer, great attention was given to the flow uniformity inside the test section. The selection of a non-uniform inlet temperature profile was in this case found not as determinant as for the stable boundary layer to improve the longitudinal uniformity, while the application of a calibrated capping inversion considerably improved the lateral uniformity. The non-dimensional vertical profiles of turbulent quantities and heat fluxes, did not seem to be influenced by roughness (by a comparison with Hancock et al., 2013), suggesting, again, that changes of roughness produce only local effects in the generated boundary layer. Good agreement is also shown with Ohya and Uchida (2004), in which no spires were employed.

Acknowledgments

This work was funded by the EPSRC (grant EP/P000029/1) and by the Department of Mechanical Engineering Sciences (University of Surrey). The authors confirm that all wind tunnel data are fully available without restriction from <https://doi.org/10.6084/m9.figshare.5993572>.

References

- Argyle, P., Watson, S., 2012. A study of the surface layer atmospheric stability at two UK offshore sites, in: European wind energy association conference, pp. 16–19.
- Arya, S.P.S., Plate, E.J., 1969. Modeling of the Stably Stratified Atmospheric Boundary Layer. doi:10.1175/1520-0469(1969)26<656:MOTSSA>2.0.CO;2.

- 656 Caughey, S.J., Palmer, S.G., 1979. Some aspects of turbulence structure through
657 the depth of the convective boundary layer. *Quarterly Journal of the Royal*
658 *Meteorological Society* 105, 811–827. doi:10.1002/qj.49710544606.
- 659 Caughey, S.J., Wyngaard, J.C., Kaimal, J.C., 1979. Turbulence in the evolving
660 stable boundary layer. *J. Atmos. Sci.* 36, 1041–1052. doi:10.1175/
661 1520-0469(1979)036<1041:TITESB>2.0.CO;2.
- 662 Cheng, H., Castro, I., 2002. Near wall flow development after a step change in
663 surface roughness. *Boundary-layer Meteorology* 105, 411–432. doi:10.1023/
664 A:1020355306788.
- 665 Cheng, H., Hayden, P., Robins, A.G., Castro, I.P., 2007. Flow over cube arrays
666 of different packing densities. *Journal of Wind Engineering and Industrial*
667 *Aerodynamics* 95, 715–740. doi:10.1016/j.jweia.2007.01.004.
- 668 Counihan, J., 1969. An improved method of simulating an atmospheric
669 boundary layer in a wind tunnel. *Atmospheric Environment* 3, 197–214.
670 doi:10.1016/0004-6981(69)90008-0.
- 671 Fedorovich, E., 2004. Dispersion of passive tracer in the atmospheric con-
672 vective boundary layer with wind shears: A review of laboratory and nu-
673 merical model studies. *Meteorology and Atmospheric Physics* 87, 3–21.
674 doi:10.1007/s00703-003-0058-3.
- 675 Fedorovich, E., Kaiser, R., 1998. Wind tunnel model study of turbulence
676 regime in the atmospheric convective boundary layer, in: *Buoyant convec-*
677 *tion in geophysical flows*. Springer Netherlands, pp. 327–370. doi:10.1007/
678 978-94-011-5058-3.
- 679 Fedorovich, E., Nieuwstadt, F.T.M., Kaiser, R., 2001. Numerical and Labo-
680 ratory Study of Horizontally Evolving Convective Boundary Layer. Part II:
681 Effects of Elevated Wind Shear and Surface Roughness. *Journal of the At-*
682 *mospheric Sciences* 58, 546–560. doi:10.1175/1520-0469(2001)058<0546:
683 NALSOH>2.0.CO;2.

- 684 Fedorovich, E., Rau, M., Kaiser, R., Plate, E., 1996. Wind Tunnel Study of
685 Turbulent Flow Structure in the Convective Boundary Layer Capped by a
686 Temperature Inversion. doi:10.1175/1520-0469(1996)053<1273:WTSOTF>
687 2.0.CO;2.
- 688 Flores, O., Riley, J.J., 2011. Analysis of Turbulence Collapse in the Stably
689 Stratified Surface Layer Using Direct Numerical Simulation. *Boundary-Layer*
690 *Meteorology* 139, 241–259. doi:10.1175/1520-0469(1969)26<656:MOTSSA>
691 2.0.CO;2.
- 692 Hancock, P.E., Hayden, P., 2016. Wind-tunnel simulation of stably stratified
693 atmospheric boundary layers. *Journal of Physics: Conference Series* 753,
694 032012. doi:10.1088/1742-6596/753/3/032012.
- 695 Hancock, P.E., Hayden, P., 2018. Wind-Tunnel Simulation of Weakly and Mod-
696 erately Stable Atmospheric Boundary Layers. *Boundary-Layer Meteorology*
697 , 1–29doi:10.1007/s10546-018-0337-7.
- 698 Hancock, P.E., Pascheke, F., 2014. Wind-Tunnel Simulation of the Wake of
699 a Large Wind Turbine in a Stable Boundary Layer. Part 1: The Boundary-
700 Layer Simulation. *Boundary-Layer Meteorology* 151, 3–21. doi:10.1007/
701 s10546-013-9886-y.
- 702 Hancock, P.E., Zhang, S., Hayden, P., 2013. A Wind-Tunnel
703 Artificially-Thickened Simulated Weakly Unstable Atmospheric Bound-
704 ary Layer. *Boundary-Layer Meteorology* 149, 355–380. doi:10.1007/
705 s10546-013-9847-5.
- 706 Heist, D.K., Castro, I.P., 1998. Combined laser-doppler and cold wire anemom-
707 etry for turbulent heat flux measurement. *Experiments in Fluids* 24, 375–381.
708 doi:10.1007/s003480050186.
- 709 Hibberd, M.F., Sawford, B.L., 1994. A Saline Laboratory Model of the Plane-
710 tary Convective Boundary Layer. *Boundary-Layer Meteorology* 67, 229–250.
711 doi:https://doi.org/10.1007/BF00713143.

- 712 Högström, U., 1988. Non-Dimensional Wind and Temperature Profiles in the
713 Atmospheric Surface Layer: A Re-Evaluation. *Boundary-Layer Meteorology*
714 42, 55–78. doi:10.1007/978-94-009-2935-7_6.
- 715 Irwin, H.P.A.H., 1981. The design of spires for wind simulation. *Journal of*
716 *Wind Engineering and Industrial Aerodynamics* 7, 361–366. doi:10.1016/
717 0167-6105(81)90058-1.
- 718 Kaimal, J.C., 1973. Turbulence spectra, length scales and structure parameters
719 in the stable surface layer. *Boundary-Layer Meteorology* 4, 289–309. doi:10.
720 1007/BF02265239.
- 721 Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric boundary layer flows: their
722 structure and measurement. volume 72. Oxford University Press. doi:10.
723 1016/0021-9169(95)90002-0.
- 724 Meroney, R.N., 1998. Wind tunnel simulation of convective boundary layer
725 phenomena: simulation criteria and operating ranges of laboratory facilities.,
726 in: et al. Plate, E. (Ed.), *Buoyant convection in geophysical flows*. Kluwer,
727 pp. 313–326. doi:10.1007/978-94-011-5058-3_14.
- 728 Monin, A.S., Obukhov, A.M., 1954. Basic laws of turbulent mixing in the
729 surface layer of the atmosphere. *Contrib. Geophys. Inst. Acad. Sci. USSR* 24,
730 163–187.
- 731 Ogawa, Y., Diosey, P.G., Uehara, K., Ueda, H., 1985. Wind tunnel observation
732 of flow and diffusion under stable stratification. *Atmospheric Environment*
733 (1967) 19, 65–74. doi:10.1016/0004-6981(85)90136-2.
- 734 Ohya, Y., 2001. Wind-tunnel study of atmospheric stable boundary layers over
735 a rough surface. *Boundary-Layer Meteorology* 98, 57–82. doi:10.1023/A:
736 1018767829067.
- 737 Ohya, Y., Neff, D.E., Meroney, R.N., 1997. Turbulence Structure in a Stratified
738 Boundary Layer Under Stable Conditions. *Boundary-Layer Meteorology* 83,
739 139–162. doi:10.1023/A:1000205523873.

- 740 Ohya, Y., Uchida, T., 2003. Turbulence structure of stable boundary layers with
741 a near-linear temperature profile. *Boundary-Layer Meteorology* 108, 19–38.
742 doi:10.1023/A:1023069316164.
- 743 Ohya, Y., Uchida, T., 2004. Laboratory and numerical studies of the convective
744 boundary layer capped by a strong inversion. *Boundary-Layer Meteorology*
745 112, 223–240. doi:10.1023/B:BOUN.0000027913.22130.73.
- 746 Oke, T.R., 1987. *Boundary layer climates*. 2nd ed., London. doi:10.1016/
747 0012-8252(90)90005-G.
- 748 Robins, A., Castro, I., Hayden, P., Steggel, N., Contini, D., Heist, D., John
749 Taylor, T., 2001. A wind tunnel study of dense gas dispersion in a stable
750 boundary layer over a rough surface. *Atmospheric Environment* 35, 2253–
751 2263. doi:10.1016/S1352-2310(01)00073-5.
- 752 Snyder, W.H., Castro, I.P., 2002. The critical Reynolds number for rough-wall
753 boundary layers. *Journal of Wind Engineering and Industrial Aerodynamics*
754 90, 41–54. doi:10.1016/S0167-6105(01)00114-3.
- 755 Stull, R.B., 1988. *An Introduction to Boundary Layer Meteorology*. volume 13.
756 Springer Netherlands. doi:10.1007/978-94-009-3027-8.
- 757 Wilczak, J.M., Phillips, M.S., 1986. An indirect Estimation of Convec-
758 tive Boundary Layer Structure for Use in Pollution Dispersion models.
759 *Journal of climate and applied meteorology* 25, 1609–1624. doi:10.1175/
760 1520-0450(1986)025<1609:AIEOCB>2.0.CO;2.
- 761 Williams, O., Hohman, T., Van Buren, T., Bou-Zeid, E., Smits, A.J., 2017. The
762 effect of stable thermal stratification on turbulent boundary layer statistics.
763 *Journal of Fluid Mechanics* 812, 1039–1075. doi:10.1017/jfm.2016.781.
- 764 Willis, G.E., Deardorff, J.W., 1974. A Laboratory Model of the Unstable Plan-
765 etary Boundary Layer. *Journal of the Atmospheric Sciences* 31, 1297–1307.
766 doi:10.1175/1520-0469(1974)031<1297:ALMOTU>2.0.CO;2.

767 Wood, C.R., Lacser, A., Barlow, J.F., Padhra, A., Belcher, S.E., Nemitz, E.,
768 Helfter, C., Famulari, D., Grimmond, C.S.B., 2010. Turbulent Flow at 190 m
769 Height Above London During 2006-2008: A Climatology and the Applicability
770 of Similarity Theory. *Boundary-Layer Meteorology* 137, 77–96. doi:10.1007/
771 s10546-010-9516-x.