

Investigating the Influence of Stepped Roofs on Wind Dynamics Using Large Eddy Simulation

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Abstract

This study investigates airflow and turbulence within varying roof configurations in urban boundary layers by using the parallelized large-eddy simulation model(PALM). Key findings reveal stark contrasts in airflow between stepped and flat roof arrangements, with the former presenting dual counter-rotating vortices and enhanced vertical motion in one street, while the latter exhibited a primary vortex and several secondary vortices. Additionally, normalized turbulence kinetic energy(TKE) was markedly lower in flat roof configurations, with stepped roofs fostering more significant turbulence and small-scale turbulent motion. This variability intensified with decreasing step height and quantity. Vertical profiles further disclosed considerable velocity disturbances and larger Reynolds numbers in one street of stepped roofs, affirming the roof's influence on turbulence generation and transport. Dispersive stress also displayed differing characteristics in various canyons. Turbulent momentum transport through eddies significantly dif-

fers between the windward and leeward streets of flat and stepped roofs. Further exploration into density stratification effects and scalar transport in stepped roofs would enhance practical implications.

19 *Keywords:* turbulence, wind force, stepped roof, numerical simulation

20 **1. Introduction**

21 Turbulence, a challenging question prevails ubiquitously in atmospheric phe-
22 nomena (Bourgoin et al., 2020). Characterized by chaotic and irregular fluid mo-
23 tion, turbulence poses numerous challenges in terms of understanding and study
24 (Eames and Flor, 2011). Grasping the concept of turbulence has far-reaching im-
25 plications in diverse fields including fluid physics, environmental fluid dynamics,
26 meteorology, geophysical dynamics, engineering, and astrophysics. Specifically,
27 in meteorology, turbulence serves as a fundamental factor in cloud formation, air-
28 mass mixing, heat and moisture transport in the atmosphere. It impacts boundary-
29 layer processes, aviation safety, and pollutant dispersion. In urban environments
30 or densely populated areas, airflow dictates the environmental conditions for daily
31 activities (Takemi et al., 2020). A trend towards urbanization and growth in urban
32 populations necessitates systematic research on turbulence in urban environments.
33 However, the complexity of city layouts introduces significant challenges to such
34 research (Park et al., 2015). Moreover, local urban scales are often 100 m or

35 smaller, referred to as the microscale or street scale, which complicates detailed
36 simulations (Britter and Hanna., 2013). Street canyons, as fundamental elements
37 in urban environments (Park et al., 2022), warrant special attention owing to their
38 frequent interaction with pedestrian activities. Past research extensively investi-
39 gated turbulence within street canyons via wind tunnel experiments, field obser-
40 vations, and numerical simulations (Letzel et al., 2008; Xie and Castro, 2009;
41 Nakayama et al., 2011; Park et al., 2012; Zhong et al., 2015; Kwak et al., 2016;
42 Duan et al., 2019).

43 Studies have highlighted that an array of factors profoundly influences turbu-
44 lence within street canyons. Key elements characterizing turbulence generation
45 include aspects like urban scale and the ratios of street dimensions (Hang et al.,
46 2009, 2010, 2012), the ratios of frontal and plan areas (Michioka et al., 2014), fluc-
47 tuations in building heights (Nakayama et al., 2011; Chen et al., 2017), disparities
48 in building geometries (Llaguno-Munitxa and Bou-Zeid, 2018), the directionality
49 of wind (Buccolieri et al., 2015) and the thermal effects(Duan and Takemi, 2021;
50 Mouzourides et al., 2022). Moreover, the characteristics and designs of building
51 roofs, particularly variations in their shapes and heights, are increasingly being
52 recognized as significant factors affecting turbulence within these urban environ-
53 ments(Rafailidis, 1997; Dirss et al., 2014; Garau et al., 2018; Chahardoli et al.,

54 2022).

55 The quality of air within street canyons is contingent upon the exchange of
56 air with the overlying atmosphere, a process predominantly dictated by the shear
57 layer generated at the roof level. Consequently, the configuration of the roof
58 emerges as a critical factor influencing the ventilation within the canyon(Garau
59 et al., 2018). To date, considerable advancements have been made regarding the
60 influence of roof shapes on urban turbulence and air pollution. Liu et al.(2020)
61 delved into the analysis of airflow surrounding a single building model with a va-
62 riety of roof shapes. Their findings underscored the crucial role of the roof shape
63 in dictating efficiency, with flat roofs outperforming those with more intricate geo-
64 metrical configurations. Furthermore, they observed that the pedestrian-level flow
65 was markedly impacted by the variations in roof shapes. Chahardoli et al.(2022)
66 found that the vortex size influences particle concentration around buildings de-
67 pending on the building shape. Garau et at.(2018)'s finding indicate that gable
68 roofs often lead to a postponement in the transition from skimming-flow to the
69 wake-interference regime and facilitate the development of a deeper, more turbu-
70 lent roughness layer. The introduction of a gable roof remarkably enhances the
71 momentum flux, particularly in situations of high packing density. The exchange
72 of air is superior compared to buildings with flat roofs, with the advantageous

73 impact being more noticeable for narrower canyons.

74 However, even though previous research has investigated turbulence in obsta-
75 cles configured with various roof shapes(Huang et al.(2009), Takano and Monen
76 (2015)), including Chahardoli et al.(2022)’s work involving numerical simulations
77 of turbulence in obstacles with eight different roof configurations, the majority of
78 simulations tend to focus on flat roofs and gable roofs. Meanwhile, stepped roofs,
79 which are prevalent in real-world scenarios including but not limited to Europe
80 and Asia (see Figure 1), often get overlooked. Considering the aforementioned
81 significance of roof shape on turbulence within street canyons, understanding the
82 impact of stepped roofs on urban turbulence is not only crucial but also carries
83 practical implications.

84 In order to deepen our understanding of the combined impacts of various
85 stepped roofs on turbulent flows within street canyons and the roughness sub-
86 layer, we utilize a Large-Eddy Simulation (LES) modeling approach to compare
87 the turbulence over different stepped roof obstacles with that over flat roof obsta-
88 cles. LES, proven by a number of previous studies (Kanda, 2006; Kanda et al.,
89 2004, 2013; Nakayama et al., 2011; Takemi et al., 2020; Duan et al., 2020, 2022),
90 provides dependable precision in the exploration of urban turbulence and offers
91 flexibility for convenient parameter adjustments.

92 The organization of this study is as follows: Section II provides an overview
93 of the research methodology, including of the employment of a Large-Eddy Sim-
94 ulation (LES) model and the configuration of an urban model, along with in-depth
95 descriptions of the parameters utilized in the LES model. Section III establishes
96 the reliability of the LES model by juxtaposing it with wind tunnel experimental
97 data. Section IV reveals the simulation outcomes, with comprehensive analyses of
98 mean flow, normalized TKE, the normalized mean and turbulence vertical profiles
99 and wind comfort to the left and right street streets. Finally, Section V summarizes
100 the present study by encapsulating the findings from the simulations and offering
101 perspectives on potential avenues for future research.

102 **2. Methodology**

103 *2.1. Numerical model*

104 In this study, the PALM version 6.0(formerly an abbreviation for Parallelized
105 Large-eddy Simulation Model and now an independent name) was adopted for the
106 numerical simulation of turbulent flow and pollutant dispersion in street canyons
107 with different roofs of roughness blocks. As demonstrated in previous research,
108 including obstacle arrays, street canyons, and realistic urban areas, PALM has
109 been broadly used in studies regarding urban flow and pollutant dispersion (Maronga
110 et al. 2020).



(a) An European hotel, © Pixabay GmbH Co., used with permission.



(b) A traditional Chinese house in south of Anhui province © Bin Jiao, used with permission.

Figure 1: Stepped roofs in traditional European and Asian area.

111 The PALM model functions by resolving a set of Navier-Stokes equations
112 with the Boussinesq approximation. Prognostic variables, including velocity com-
113 ponents (u, v, w), passive scalar concentration (s), and subfilter-scale turbulence
114 kinetic energy (TKE), are discretized on an Arakawa C-grid, a staggered grid
115 (Arakawa and Lamb 1977). The magnitudes of velocity, namely u , v , and w , de-
116 note the components in the streamwise, spanwise, and vertical directions, respec-
117 tively. The model applies a third-order Runge-Kutta scheme for time integration,
118 while a fifth-order upwind-biased scheme is used for the discretization of advec-
119 tion terms (Maronga et al. 2015; Letzel et al. 2008).

120 Subgrid-scale (SGS) eddies are parameterized using the 1.5-order TKE scheme
121 for calculating the SGS fluxes of momentum and scalars (Deardorff 1980; Maronga
122 et al. 2015). The model has been verified against multiple field measurements and
123 wind tunnel experiments, revealing a favorable correlation between the simula-
124 tions and the actual measurements (Letzel et al. 2008; Maronga et al. 2013;
125 Yaghoobian et al. 2014; Han et al. 2018).

126 In the paper by Manago et al. 2020, the flow are simulated using large-
127 eddy simulation (LES) and the implicitly filtered non-hydrostatic, incompressible
128 Boussinesq equations, viz.,

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial \tilde{\pi}^*}{\partial x_i} - \frac{\partial}{\partial x_j} \left(\tilde{u}'_i \tilde{u}'_j - \frac{2}{3} \delta_{ij} \tilde{e} \right), \quad (1)$$

where the tilde denotes resolved-scale variables. In this formula, the prime symbol (') represents a derivative, not a deviation from the average value. For the dynamical variables, $\tilde{u}_i = (u, v, w)$ are the velocity components corresponding to the spatial coordinates $x_i = (x, y, z)$, $\tilde{u}'_i \tilde{u}'_j$ is the (subgrid-scale) SGS stress tensor where the double primes denote SGS variables; $\tilde{e} = \frac{1}{2} \tilde{u}'_i \tilde{u}'_i$ is the SGS turbulence kinetic energy (TKE);

$\tilde{\pi}^* = \pi^* + \frac{2}{3} \rho_0 e$ is the modified perturbation pressure (π^*); ρ_0 is the reference density.

2.2. Geometry of roughness obstacle

To effectively and accurately assess how the roofs of obstacles impact airflow within the urban canopy layer and street canyons, a simplified two-dimensional model of a roughness block was devised. This model also facilitates the exploration of turbulent structures within the spanwise direction of street canyons. The computational domain spans 60m in the streamwise direction (x), 20m in the spanwise direction (y), and 40m in the vertical direction (z). The typical obstacle height, denoted as H , is 10 meters. This means that the dimensions of the computational domain are $6H$, $2H$, and $4H$ in the x , y , and z directions, respectively.

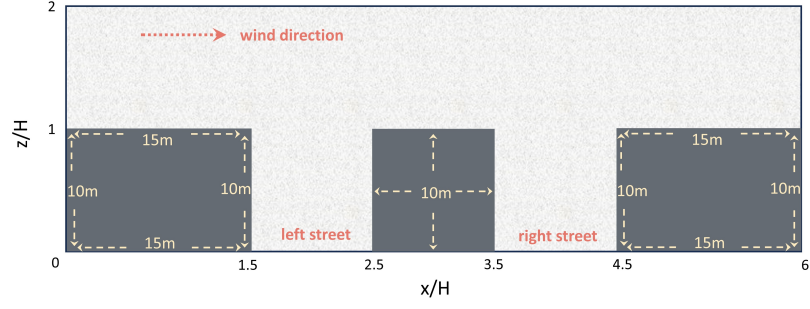
146 Employing a traditional three-dimensional rectangular configuration, the compu-
147 tational grid utilizes a 0.25-meter distance in the Δx , Δy , and Δz directions, thereby
148 constituting a total of 3,072,000 grid cells.

149 To elucidate the influence of different step heights in stepped-roof structures
150 on turbulence, in this context, we employ l_{rs} that represents the ratio of one step
151 height(H_{rs}) to the standard obstacle height:

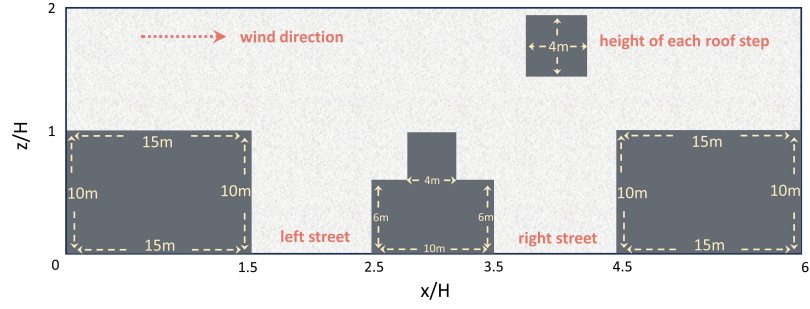
$$l_{rs} = H_{rs}/H. \quad (2)$$

152 Figure 2 presents the configurations of the obstacles utilized in four different
153 simulation experiments. Figure 2a depicts the obstacles with a flat roof having the
154 standard height. Figures 2b, 2c, and 2d, on the other hand, illustrate the obstacles
155 with stepped roofs at varying one roof height. The roof sections in these figures
156 are highlighted in red.

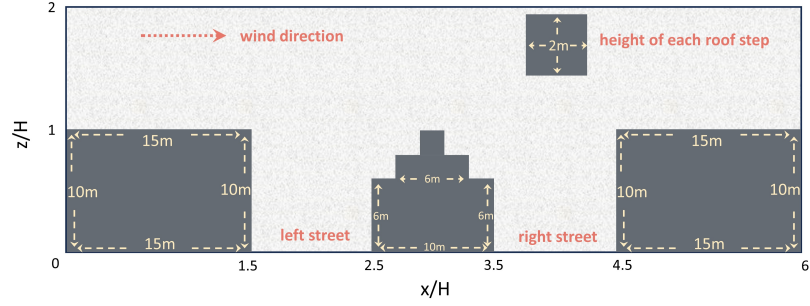
157 This model operates by assuming that the stabilities in the strictly neutral con-
158 ditions. The boundary conditions entail the application of Dirichlet conditions
159 at the left boundary (i.e., the inlet), while the right boundary (i.e., the outlet)
160 adopts radiation boundary conditions. A cyclic condition is applied at the north
161 and south boundaries, or the lateral surfaces. The bottom boundary condition is
162 a no-slip boundary condition, while the top boundary condition is a Neumann



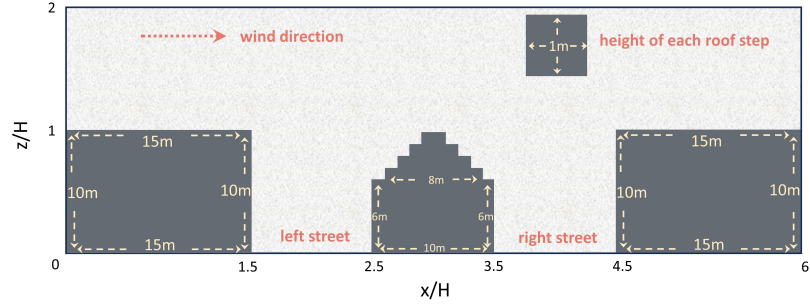
(a) S_1 , flat roof.



(b) S_2 , stepped roof with $l_{rs} = 0.4H$.



(c) S_3 , stepped roof with $l_{rs} = 0.2H$.



(d) S_4 , stepped roof with $l_{rs} = 0.1H$.

Figure 2: The distribution of obstacles for four different roofs.

163 boundary condition. The boundary conditions close to the wall are defined using
164 parameters derived from the Monin-Obukhov similarity theory instead of using a
165 standard wall function. These parameters include a roughness length of $z_0 = 0.1m$
166 and a layer of constant flux that extends from the wall to the first point on the grid.

167 In the simulation, a turbulent inflow technique is employed , which involves
168 the recirculation of turbulent flow from the primary outlet back to the inlet. Specif-
169 ically, similar to the approach of Nakayama et al., 2011, we recycled the wind
170 profile of the airflow passing through obstacles in a precursor run to obtain a more
171 realistic inflow wind profile. The recycling technique initially proposed by Lund
172 et al.(1998) and further refined by Kataoka and Mizuno (2002). This recycling
173 procedure is layered onto the velocity profile created by the precursor flow, which
174 assists in reaching statistical equilibrium and fosters the development of adequate
175 turbulence. The recycling plane is located near the outlet.

176 The precursor run lasts for a duration of 5 hours and employs periodic bound-
177 aries, and is driven by an external pressure gradient having the magnitude $dp/dx =$
178 $-6 \times 10^{-4} \text{ Pa m}^{-1}$. The prevailing speed U_f is about 1.36 m s^{-1} and the Reynolds
179 number $Re (= U_f H / \nu)$ is about 1.12×10^6 . The total simulation time is 4800 sec-
180 onds, which includes an initial 1800-second spin-up period to stabilize the flow
181 field physically and ensure the precision of the simulation results. The data collec-

tion involves sampling every 6 seconds over a period of 3000 seconds, and these data are then used for subsequent analysis. We conducted a time series analysis on the data spanning 3000 seconds, demonstrating the complete development of turbulence and attainment of statistical equilibrium (figure omitted).

Figure 3 presents the Fourier spectrum and wavelet spectrum of vertical fluctuations. Within the dashed box, although the Fourier spectrum shows some oscillations, the wavelet spectrum is relatively smooth. Both spectra closely follow the "-5/3" power law. Specifically, in this interval, the least squares fit of the Fourier spectrum is -1.68, and the wavelet spectrum is -1.74, both of which are very close to the theoretical value of -1.67. Furthermore, this interval clearly falls within the inertial subrange predicted by Kolmogorov (10^{-3} to 10^3), providing further evidence of achieving turbulence equilibrium.

Table 1 provides an inclusive summary of the parameters and the urban-like geometry for easy reference.

In the notation used within the paper, $\langle \rangle$ denotes spatial averaging, which includes both spanwise and streamwise directions, $(\overline{})$ represents time averaging, and $(\prime)$ signifies the deviation from the average value.

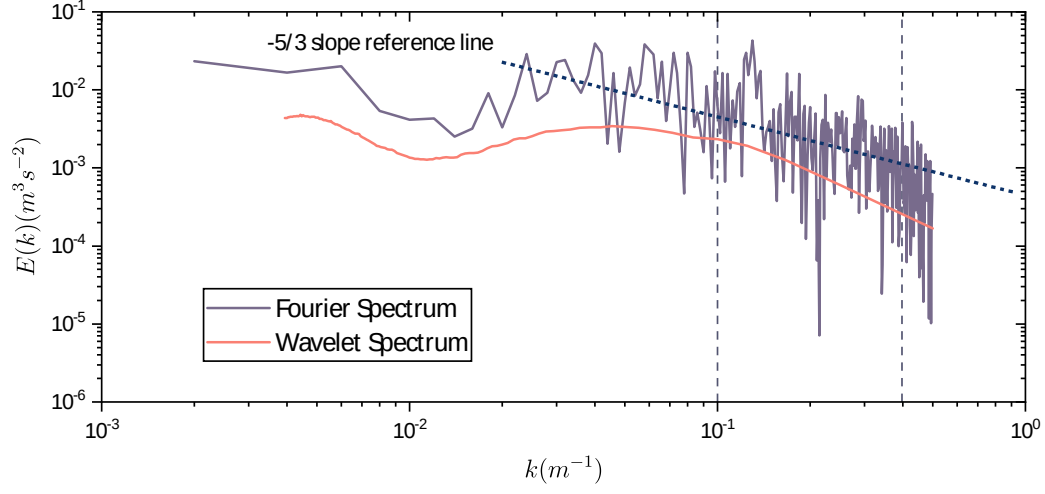


Figure 3: Energy spectrum of vertical fluctuation velocity $x/h=2$, $y/h=0.5$, $z/H=0.5$.

Table 1: **Domain dimensions**

Parameter	Attribute	Set-up	Unit
H_N	Normal obstacle height	10	m
H_{rs}	one step height	1/2/4	m
L_x	Domain size in the x -direction	60	m
L_y	Domain size in the y -direction	20	m
L_z	Domain size in the z -direction	40	m
Δx	Gird size in the x -direction	0.25	m
Δy	Gird size in the y -direction	0.25	m
Δz	Gird size in the z -direction	0.25	m
$L_x/\Delta x$	Number of grids in the x -direction	240	number
$L_y/\Delta y$	Number of grids in the y -direction	80	number
$L_z/\Delta z$	Number of grids in the z -direction	160	number
σ_{grids}	Number of grids	3,072,000	number
z_0	Roughness length	0.1	m

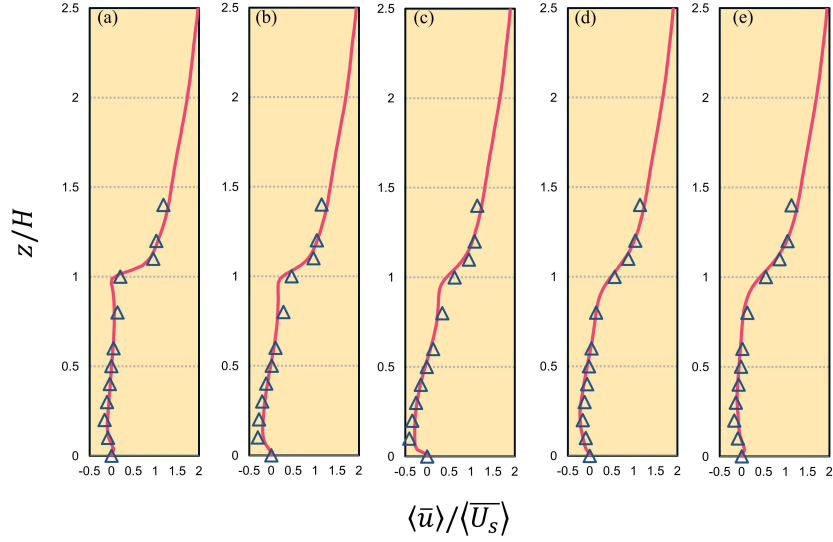


Figure 4: Normalised mean streamwise velocity profiles from the simulation results (red solid curve) and wind tunnel measurement results (blue hollow triangle). $\langle \bar{U}_s \rangle$ represents the stream-wise velocity averaged over the shear layer ($1 \leq z/H \leq 1.5$, about 0.8 m s^{-1}), and a, b, c, d, e are located at $3.6H$, $3.75H$, $4.0H$, $4.25H$, and $4.4H$, respectively.

3. Validation

While numerous studies have established the precision of the PALM model in replicating urban turbulence, juxtaposing these simulation outcomes with data from wind-tunnel measurements remains essential for affirming the trustworthiness of the present simulations.

Simulation measurement No. 1 (S_1) was deliberately chosen for correlation with wind tunnel measurements by employing an identical normalized obstacle height set-up. Figure 4 illustrates the comparison between the LES simulation findings and the wind tunnel data collected from a previous research (Brown

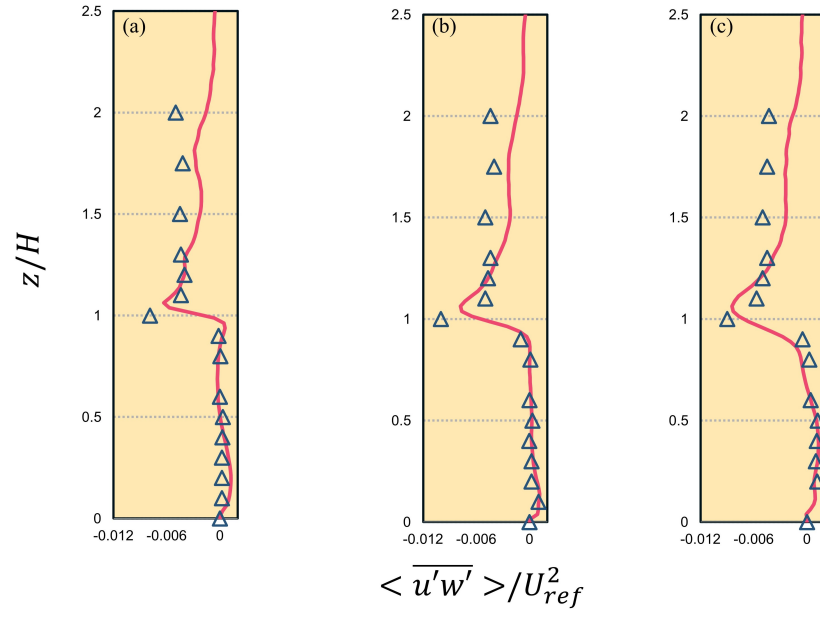


Figure 5: Normalised Mean Reynolds stress velocity profiles from the simulation results (red solid curve) and wind tunnel measurement results (blue hollow triangle) at $3.75H$, $4.0H$, $4.25H$.

208 2000). To verify the credibility of the LES model, vertical profiles of normalized
209 streamwise wind speed were utilized at various characteristic points within the
210 street canyon.

211 The LES findings demonstrate a promising concordance with the wind tun-
212 nel experiment results at five separate points in the streamwise direction, namely,
213 $3.6H$, $3.75H$, $4.0H$, $4.25H$, and $4.4H$. Among these comparisons, the LES out-
214 comes for $3.75H$ and $4.0H$ near the ground are slightly undervalued, aligning with
215 the findings of Duan and Ngan (2018). This minor discrepancy is ascribed to the
216 roughness length set at $0.1m$ (see Table 1), representing a highly rough surface in
217 contrast to the surfaces in the wind-tunnel measurements.

218 To ensure the accuracy of our simulation in terms of turbulence momentum, In
219 Fig. 5, we also compared the Reynolds stress results with the wind tunnel results
220 from Michioka et al.(2011). Although the setup of our simulation is not entirely
221 identical to the wind tunnel simulations(In the Michioka's study, the inflow was
222 set over open ground, whereas in this simulation, the inflow was obstructed by an
223 obstacle.), and there are some minor discrepancies in peak values, the overall re-
224 sults were favorable, and the trends were generally consistent. This demonstrates
225 the success of our simulation in replicating turbulence statistics.

226 Taken as a whole, the outcomes derived from the current LES model properly

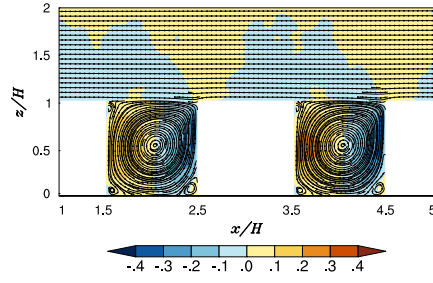
227 depict the fundamental state of the actual flow field and are deemed accurate and
228 trustworthy. Hence, the residual three simulation results can also be utilized to
229 study turbulent flow patterns in varying roof configurations.

230 **4. Numerical Results**

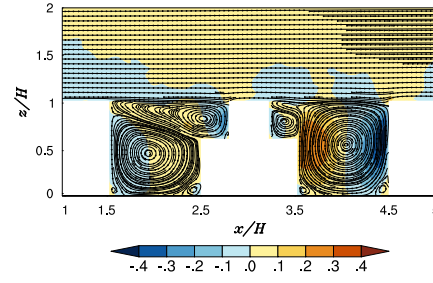
231 *4.1. Mean flow and velocity statistics*

232 This section will present the results for mean flow and velocity statistics. Here,
233 the mean flow represents the most fundamental and typical characteristics of the
234 flow field over a specific period.

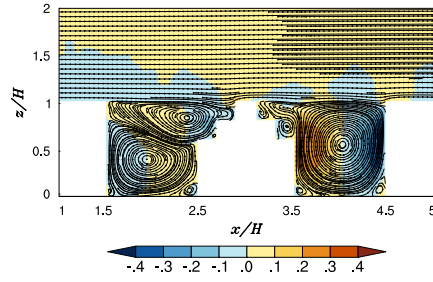
235 Firstly, Figure 6 illustrates the time-averaged flow pattern. The results shown
236 in Fig. 6a (S_1) have been confirmed in multiple studies, demonstrating the pres-
237 ence of a prominent primary vortex within the street canyon, along with three
238 smaller vortices near the corners and the obstacle height of the leeward wall. A
239 characteristic skimming flow pattern emerges, with the air predominantly flowing
240 over the obstacle tops and scarcely penetrating into the canyon interior. Stream-
241 lines above the obstacle tops exhibit a pattern akin to uniform lines. The average
242 vertical speed within the street canyon shows an approximately symmetric struc-
243 ture, with comparable velocity magnitudes on either side of the canyon centerline.
244 The vertical velocity near the leeward wall is upward, while that near the wind-
245 ward wall is downward. The basic flow form of the air on the left and right streets



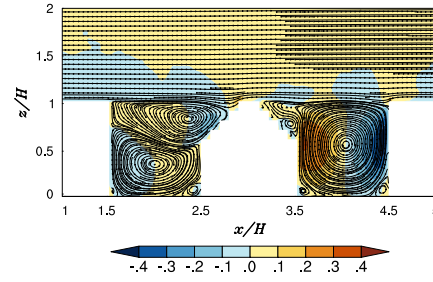
(a) S_1 , flat roof.



(b) S_2 , stepped roof with $l_{rs} = 0.4H$.



(c) S_3 , stepped roof with $l_{rs} = 0.2H$.



(d) S_4 , stepped roof with $l_{rs} = 0.1H$.

Figure 6: Spanwise and temporally averaged mean flow for the case of (a) S_1 , (b) S_2 , (c) S_3 and (d) S_4 . Arrows indicate streamlines and color shadings denote the magnitude of time-averaged vertical velocity (contours, unit: $m s^{-1}$) in the $x-z$ plane.

246 are similar, although the vertical movement of the airflow in the right street is
247 slightly greater than that in the left street.

248 The remaining three results contrast significantly with those from S_1 , primarily
249 seen in the completely different flow patterns on the left and right sides of the
250 street. The most notable difference is the appearance of two primary vortices in
251 the left side of the street canyon, along with a weakening of vertical motion. The
252 larger primary vortex below is counter-clockwise, while the primary vortex in S_1 is
253 clockwise. This indicates that in the left street canyon with flat roofs and stepped
254 roofs, the stark contrast in flow direction has a potent impact on momentum and
255 scalar transport within the street canyon. Meanwhile, in the right street canyon,
256 compared to S_1 , the vertical movement of the airflow has notably strengthened.
257 Additionally, a secondary vortex forms at the top left corner, near the stepped
258 roof, varying according to different roof shapes.

259 The results from S_2 , S_3 , and S_4 are generally similar, but they show minor
260 variations according to the differences in l_{rs} . As l_{rs} decreases, the vortex in the
261 left bottom corner above the left street becomes larger, and the extreme value areas
262 of vertical motion on the right side also grow. Specific numerical values can be
263 found in Fig. 7, which will be described later.

264 Figure 7 illustrates the specific magnitudes of updrafts and downdrafts on both

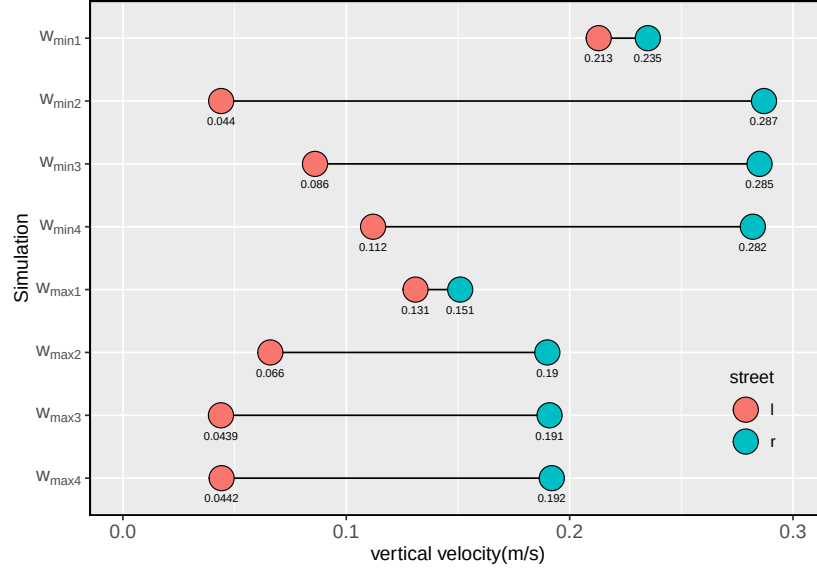


Figure 7: Maximum absolute values of time- and spanwise-averaged vertical velocity below the obstacle height in four different simulations, where vertical velocity w_{max} is positive and w_{min} is negative (unit: $m s^{-1}$).

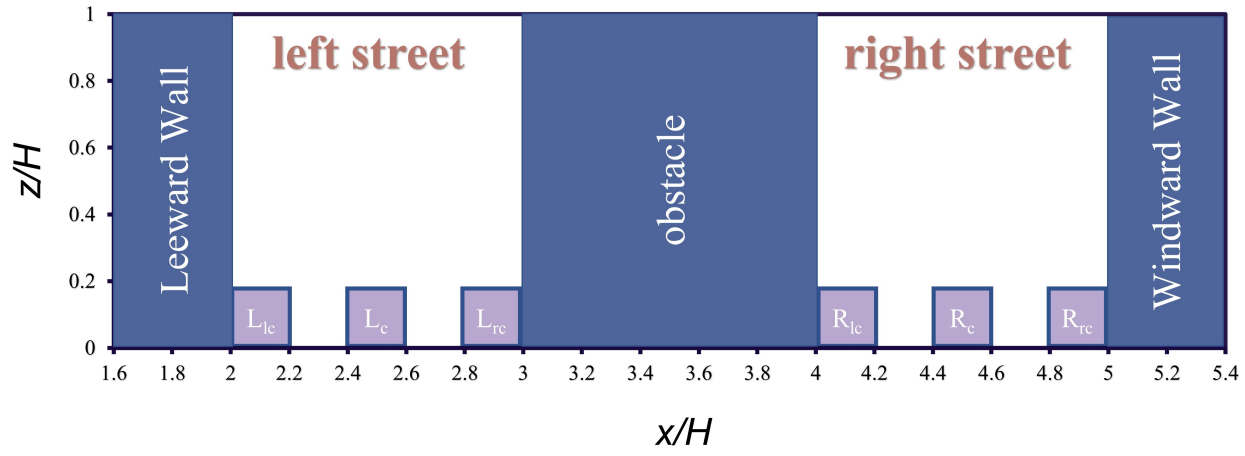
265 sides of the street in four simulations. From the length of the lines connecting the
 266 red and green balls, we can clearly see that in the flat-roof scenario, the differ-
 267 ence in updrafts and downdrafts between the two sides is minimal. However, in
 268 the stepped-roof configurations, different values of l_{rs} exhibit distinct behaviors.
 269 The smaller the l_{rs} , the greater the downdraft movement on the left side of the
 270 street and the smaller it is on the right side, reducing the disparity in downdraft
 271 movements between the two sides. Regarding the updrafts, the smaller the l_{rs} , the
 272 smaller the updraft on the left side and the greater the downdraft on the right side,
 273 increasing the disparity in downdraft movements between the two sides, though

274 the results for S_3 and S_4 are relatively similar.

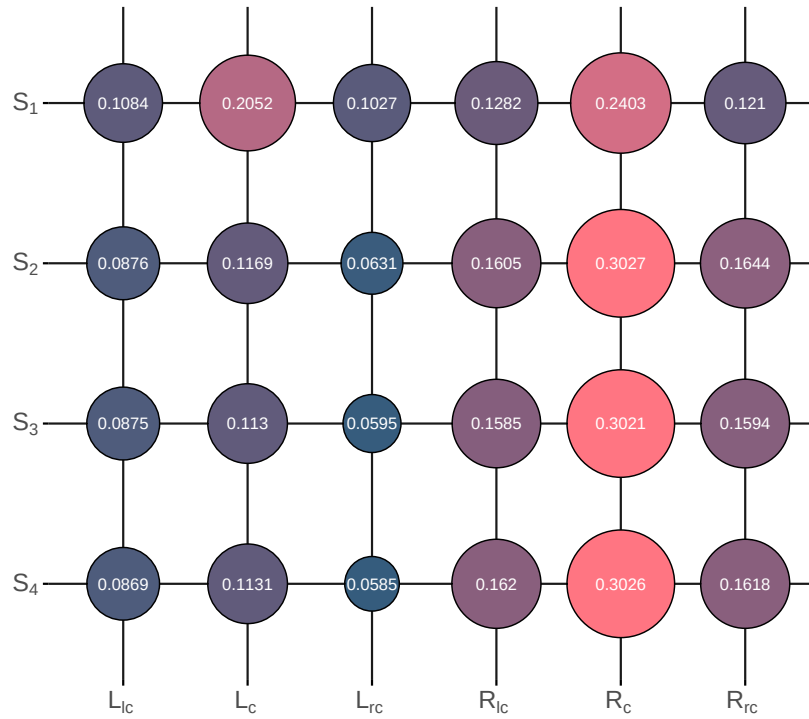
275 In addition to the vertical velocity on the streets with different roof types, we
276 also calculated the local average velocity($V = \sqrt{u^2 + v^2 + w^2}$) at the pedestrian
277 layer to explore the impact of different roof configurations on local average ve-
278 locity(Fig. 8). Specifically, we selected the left corner, center, and right corner
279 of each street at a pedestrian layer height of 1.75m as the points for statistical
280 analysis. On the left street, the average velocity under flat roofs was consistently
281 higher than that under stepped roofs, whereas on the right street, the situation was
282 reversed. Under flat roofs, the average velocity at the same locations on the left
283 and right streets showed little difference, but under stepped roofs, the differences
284 were significant, reaching 2 to 3 times. For stepped roofs, on the left street, the
285 smaller the l_{rs} , the lower the average velocity at both corners and the higher the
286 average velocity in the center, while on the right street, the differences in average
287 velocity were not significant.

288 4.2. *Turbulence statistics*

289 In this section, we discuss the turbulence statistics including the normalized
290 turbulent kinetic energy (TKE), the turbulence intensities and the skewness of the
291 u and w velocity components. The normalized TKE indicate the evolution of
292 turbulence within that time span. The TKE is defined as $TKE = \frac{1}{2}(u'^2 + v'^2 +$



(a) Six statistical areas, each area has a length of $0.2H$ and a height of $0.175H$.



(b) The spatially and temporally averaged velocity(unit: $m s^{-1}$).

Figure 8: The spatially and temporally averaged velocity at six statistical locations in the four simulations are reported. These locations are specifically positioned at the left corner, center, and right corner on both the left and right sides of the street. Each area has a length of $0.2H$ and a height of $0.175H$, representing an approximate pedestrian layer height of 1.75 meters.

293 $w'^2)$, where u' , v' and w' indicate deviations from the time-averaged measures
 294 of the velocity components in the streamwise (u), spanwise (v), and vertical (w)
 295 directions, respectively.

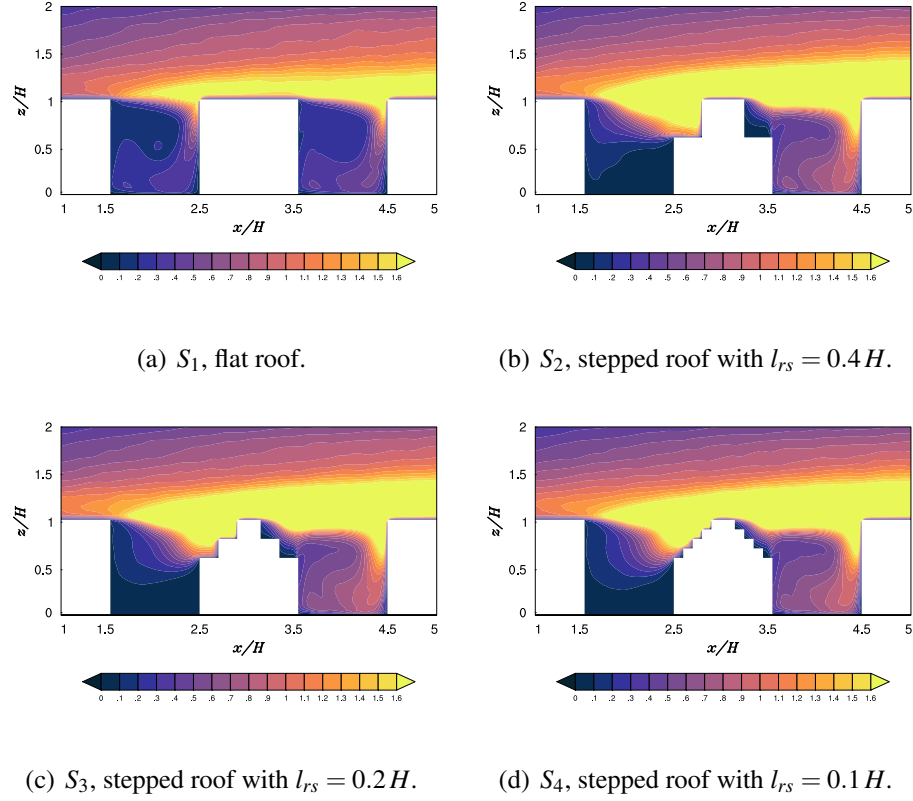


Figure 9: Normalised spanwise and temporally averaged turbulent kinetic energy($\langle \overline{TKE} \rangle / U_{ref}^2$) for (a) S_1 , (b) S_2 , (c) S_3 and (d) S_4 . The numerical values have been amplified by a factor of 100.

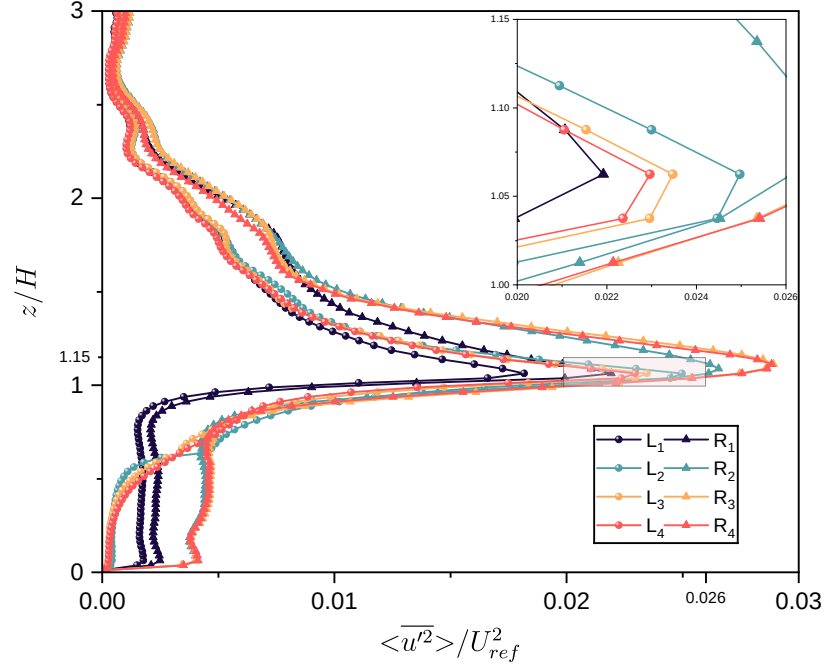
296 Figure 9 represents the normalized TKE in the four simulations. Starting with
 297 Fig. 8a (S_1), the area of high normalized TKE primarily lies between $z/H = 1.0$
 298 and $z/H = 1.2$, slightly lower at the edges of the two windward walls. Above

299 the edge of the windward wall on the right side of the street, there is a region
300 of maximum value. Similar to previous simulations, in the street canyon, the
301 normalized TKE exhibits a vortex-like appearance.

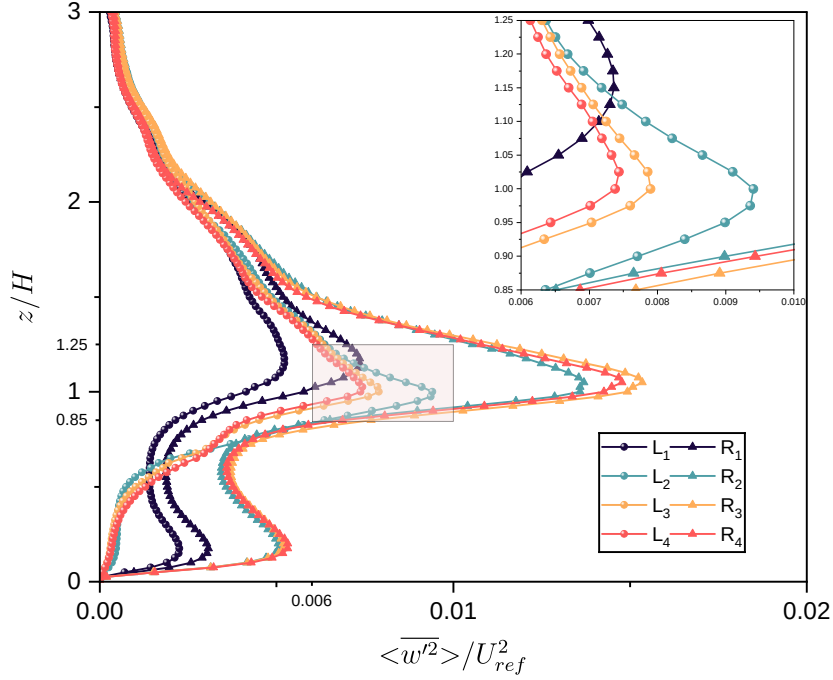
302 The simulation with the stepped roof shows a different behavior: the high-
303 value region of normalized TKE extends from the left side of the roof up to the
304 height of the first step, while the right side of the roof exhibits a low TKE re-
305 gion, especially close to the roof. Observing the TKE in the left and right street
306 canyons, the TKE in the right street canyon is significantly higher than that in the
307 left street canyon. The simulation results for the three stepped roofs are similar,
308 but according to quantitative analysis, the smaller the l_{rs} , the greater the normal-
309 ized TKE. This suggests that an increase in the number of roof steps leads to more
310 turbulent momentum generation, thereby affecting the airflow movement.

311 Overall, the simulation results for the flat roof have generally smaller normal-
312 ized TKE. For the stepped roof, as l_{rs} decreases, the maximum value area of the
313 normalized TKE gets larger, and the maximum values also increase.

314 Figure 10 indicates the vertical profiles of the mean variance of the normalised
315 streamwise velocity(Fig. 9a) and vertical velocity(Fig .9b) over the left(L) or right
316 street(R). These are averaged spatially(In the streamwise direction,1.5H-2.5H for
317 the L, and 3.5H-4.5H for R.) at each height and over time for different roofs. The



(a) Variance of streamwise velocity.



(b) Variance of vertical velocity.

Figure 10: Vertical profiles of temporally averaged, and spatially averaged variance of (a)streamwise velocity, (b)vertical velocity. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

318 numbers in the subscript of the data labels in the figure represent the number of
319 the simulation, and "L" and "R" represent the left street or the right street, respec-
320 tively. For example, " R_2 " represents the simulation results of the right street in the
321 second simulation. Note that the areas within obstacles are not included in this
322 computation. For clarity, the notation used in the following sections corresponds
323 to the specific street canyon each simulation is targeting.

324 Let's first discuss variance of streamwise velocity(Fig. 10a). In the S_1 , which
325 refers to the flat roof, the variance of the streamwise velocity for both the left and
326 right streets is noticeably smaller than in the remaining three sets, which corre-
327 spond to the stepped roof results. Furthermore, the peak values for the flat-roof
328 model are slightly lower than those for the stepped roof model. As for S_2 , S_3 , and
329 S_4 , the left and right streets demonstrate completely different outcomes. As l_{rs}
330 decreases, the peak of the variance of the streamwise velocity on the left street de-
331 creases, whereas the peak of the variance of the streamwise velocity on the right
332 street increases. When the height is lower than $z/H = 0.8$, the variance of the
333 streamwise velocity on the right street is noticeably larger than on the left street.

334 We now examine the variance of the vertical velocity(Fig. 10b). Contrary to
335 the findings concerning the variance of the streamwise velocity, the variabilities
336 of the vertical velocity show a pronounced discrepancy between the left and right

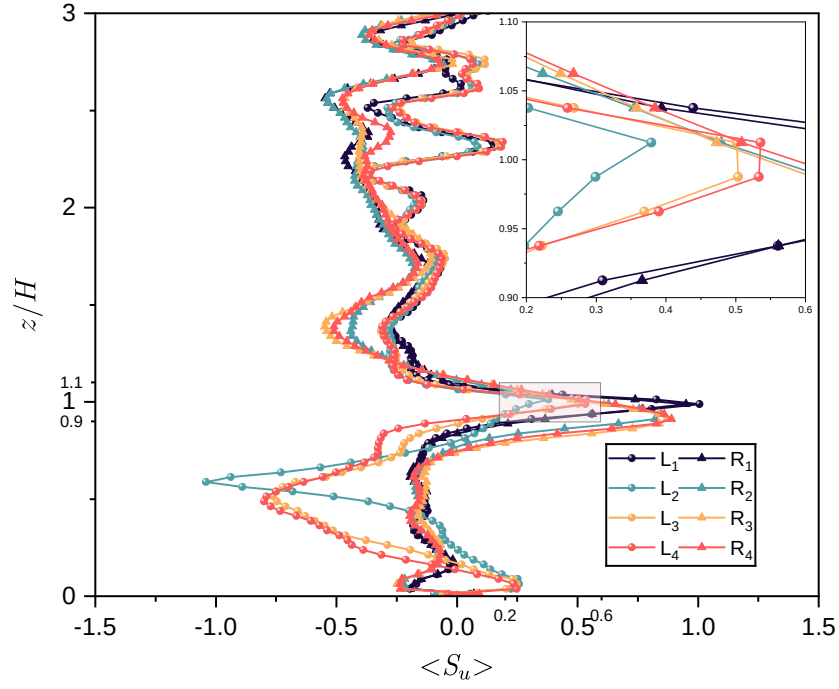
337 streets. From the results of S_1 , the peak of the variabilities of the vertical velocity
338 is smaller in the left street, hovering around 0.004, whereas it's notably higher in
339 the right street, approximating 0.008.

340 In the case of the stepped roof configurations, the difference between the left
341 and right streets is starkly pronounced. The left street's peak hovers around 0.07-
342 0.09, whereas the right street's peak ranges between 0.014 and 0.016 about two
343 to three times that of the left street. As l_{rs} decreases, the variance of the vertical
344 velocity increases on the left street, while in the right street, the results of S_2 are
345 smaller than those of S_3 and S_4 .

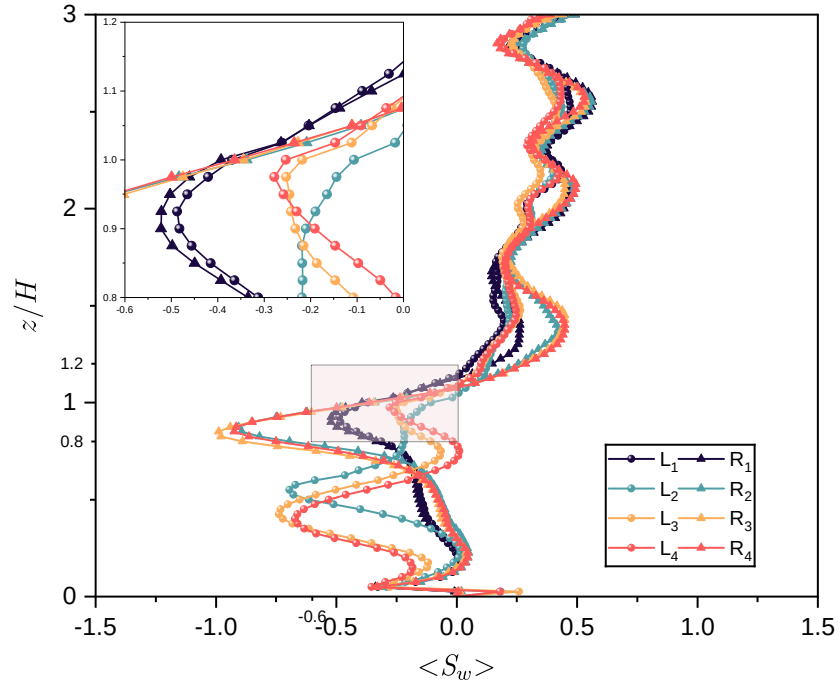
346 In Fig. 11, we discuss the third-order moment skewness of the streamwise
347 velocity($S_u = \overline{u'^3} / \sqrt{(\overline{u'^2})^3}$) and the vertical velocity($S_w = \overline{w'^3} / \sqrt{(\overline{w'^2})^3}$) in order
348 to understand the asymmetry of the streamwise velocity in the streamwise direc-
349 tion and the vertical velocity in the vertical direction.

350 For skewness of the streamwise velocity, specifically, large positive absolute
351 values indicate the presence of extremely high positive horizontal velocities over
352 short periods, while large negative absolute values indicate extremely high nega-
353 tive horizontal velocities over short periods. Our main focus is on variations near
354 and below the building height.

355 Around $z/H=1.0$, the peak values for both stepped and flat roofs occur at this



(a) Skewness of streamwise velocity.



(b) Skewness of vertical velocity.

Figure 11: Vertical profiles of temporally averaged, and spatially averaged skewness of (a) streamwise velocity, (b) vertical velocity. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

356 height. For flat roofs, this represents a typical skimming flow. The peak values
357 for both the left and right streets are close and greater than those for the stepped
358 roofs. The S_u on the right side of the stepped roofs is significantly higher than on
359 the left side, and the peak increases with larger l_{rs} .

360 At $z/H=0.6$, which is the height of the edge of the stepped roofs, all stepped
361 roofs exhibit a trough in S_u on the left street, with S_2 having the lowest value. At
362 this height, there are instances of airflow moving rapidly towards the leeward side.

363 At near-ground heights, the right street of the stepped roofs exhibits values
364 opposite to those of the left street and the flat roofs, indicating that the stepped
365 roofs significantly impact the airflow at the bottom of the left street.

366 For the skewness of vertical velocity, large positive absolute values indicate
367 the presence of extremely high vertical motions over short periods, while large
368 negative absolute values indicate extremely high downward motions over short
369 periods.

370 At $z/H=0.8$ to 0.9 , there is a trough for both the stepped and flat roofs on the
371 right street, with the flat roof's values significantly lower than those of the stepped
372 roofs.

373 At $z/H=0.3$ to 0.6 , the flat roof's results are close to zero on the left street,
374 while the stepped roofs exhibit a trough. The trough for S_2 is slightly higher than

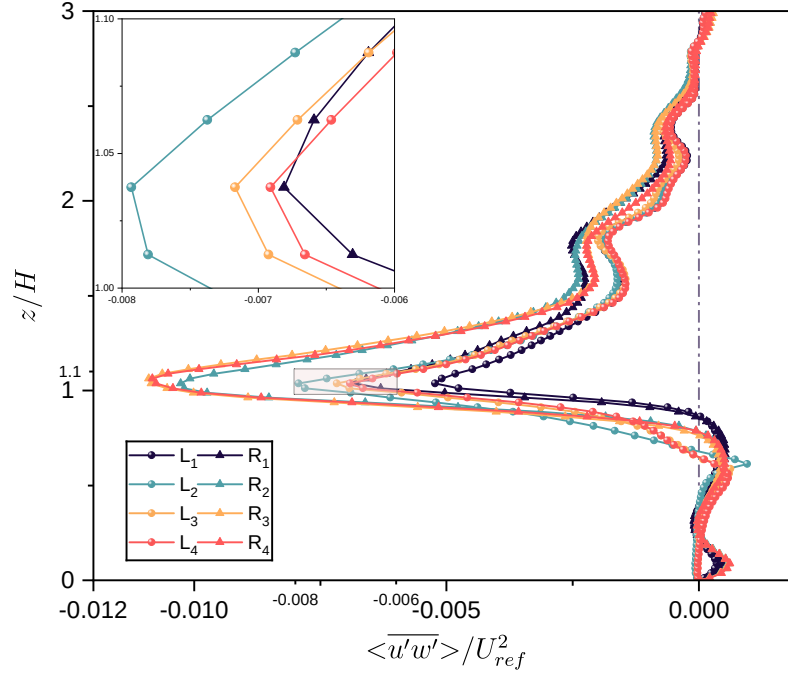


Figure 12: Vertical profiles of normalised, temporal, and spatially averaged Reynolds stress. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

those for S_3 and S_4 .

Near the ground and above $z/H=1.2$, all results show consistency. This indicates that stepped roofs impact vertical airflow in the mid-to-upper layers of the street canyon, causing more short-term but significant downward motions.

4.3. Turbulence momentum transport

Then we examined the turbulence characteristics in terms of turbulent stresses.

In Fig. 12, the vertical profiles of the mean Reynolds stress averaged horizontally

382 and temporally are shown for different roofs.

383 The Reynolds stress can be considered in two parts. At a relatively low height
384 (below $z/H = 0.1$), the results of the flat roof (S_1) show a maximum value on the
385 left street, about 0.001, whereas the Reynolds stress of the stepped roofs (S_2 , S_3 ,
386 S_4) consistently approach zero. A possible reason is that on flat roofs, airflow is
387 more likely to separate at the edges and form strong downdrafts above the street,
388 a process less pronounced with stepped roofs. This leads to stronger vertical air-
389 flows in street canyons (which is also evident in Figure 5), resulting in higher
390 Reynolds stress at the bottom of the left-side street canyon. On the right street,
391 the maximum value of S_1 is approximately 0.001, while the Reynolds stress of the
392 stepped roofs is litter higher than that of the flat roof. Near $z/h = 0.6$, all results
393 show a minor peak, among them, the results for S_2 (where l_{rs} is the largest) are
394 significantly the highest.

395 For higher elevations (between $z/H=1$ to 1.1), the Reynolds stress in all the
396 simulations presents a consistent minimum, demonstrating an enhancement in
397 the downward transport of momentum at this location. The absolute values of
398 Reynolds stress for the flat roof (S_1) on both the left and right streets are notice-
399 ably lower than those for the other stepped roof results. Similarly, as l_{rs} decreases,
400 the absolute value of Reynolds stress on the left street becomes smaller, whereas

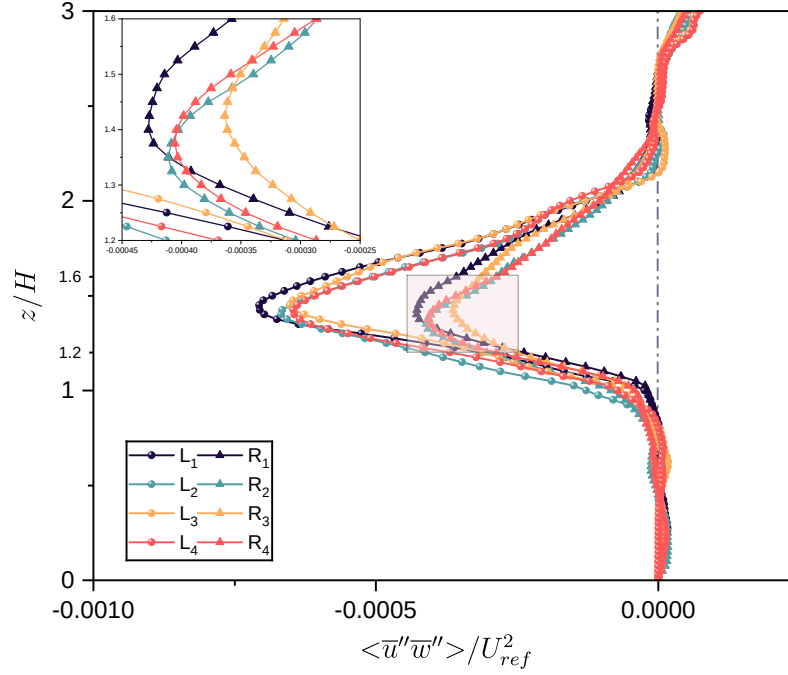


Figure 13: Vertical profiles of normalised, temporal, and spatially averaged dispersive stress. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

401 the absolute value on the right street becomes larger, however, the results for S_3
402 and S_4 are quite similar. This is consistent with the results for the variance of the
403 streamwise velocity and the variance of the vertical velocity. Overall, near this
404 height, the stepped roofs promote the downward transport of momentum, and dif-
405 ferent l_{rs} values affect the Reynolds stress of the left and right streets differently.

406 Dispersive stress refers to the stress in a fluid flow caused by spatial variations

407 in flow velocity, which is often overlooked in urban canopy studies, plays a signif-
408 icant role in turbulent transport. It has, however, attracted attention in recent stud-
409 ies (San tiago and Martilli, 2010; Giometto, 2016; Yoshida and Takemi, 2018).
410 When dispersive fluxes exhibit positive values, a countergradient flux, which sig-
411 nifies the downward transport of low momentum or the upward transport of high
412 momentum (Nazarian et al., 2020).

413 In Fig. 13. Overall, both the flat and stepped roofs show similar trends in the
414 variation of dispersive stress along the left and right streets, with a peak at a height
415 of $z/H = 1.3$ to 1.4 . However, the absolute value of the dispersive stress on the
416 left street is significantly greater than that on the right. This indicates that at this
417 height, all results show a pattern of low momentum being transported upwards
418 and high momentum being transported downwards, with the phenomenon being
419 more pronounced on the left street. Comparing the results for the three different
420 types of stepped roofs, on the left street, the larger the l_{rs} , the greater the absolute
421 value of the dispersive stress.

422 If we compare the results of Reynolds stress and dispersive stress between
423 stepped and flat roofs, we find that in the roughness layer, although the Reynolds
424 stress is lower for flat roofs, the dispersive stress is higher. This indicates that
425 in flat roofs, dispersive stress contributes more significantly to the total turbulent

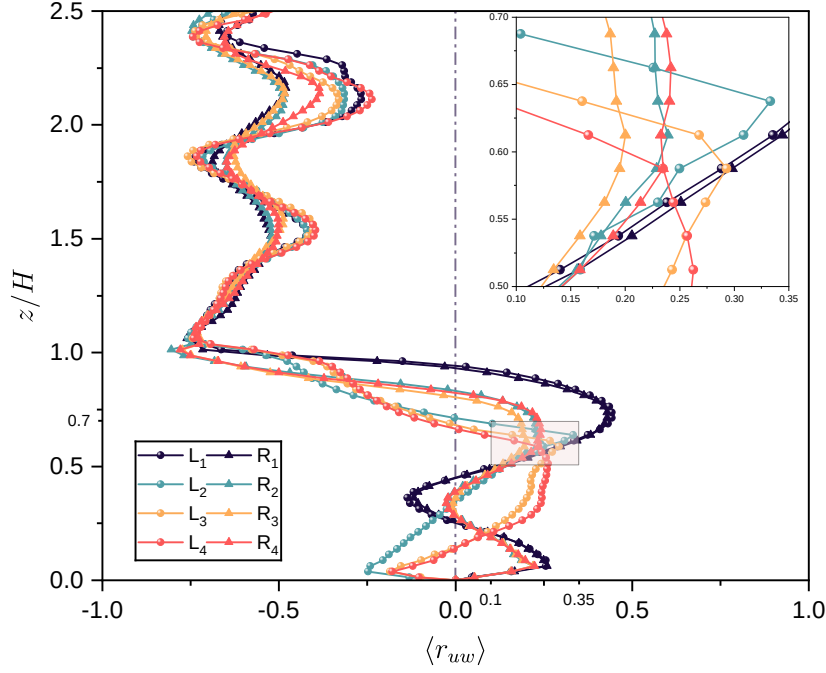


Figure 14: Vertical profiles of temporal, and spatially averaged turbulent transport efficiency. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

426 stress, whereas in stepped roofs, the contribution of dispersive stress to turbulent
 427 stress is smaller.

428 To better clarify the relationship between turbulent momentum and turbu-
 429 lent eddies, we have also analyzed the efficiency of turbulence transport($r_{uw} =$
 430 $\overline{u'w'}/\sigma_u\sigma_w$) in Fig. 14. The further the value of r_{uw} deviates from zero, the more
 431 organized the turbulence, with momentum being transported upward or downward

432 in an orderly manner through turbulent eddies. All results show minimal values
433 at heights above the obstacle, which is a very typical phenomenon in the urban
434 canopy layer, indicating highly effective momentum transfer. The main differ-
435 ences occur within the street canyons:

436 For flat roofs, the r_{uw} results are similar on both the left and right streets, show-
437 ing three peaks at heights of $z/H = 0.1$, $z/H = 0.4$, and $z/H = 0.8$. Momentum
438 is transported upwards in an orderly fashion at the lower and upper levels, while
439 it is transported downwards in an orderly fashion at the middle level.

440 The results for stepped roofs differ significantly from those of flat roofs. Near
441 the ground on the left street, turbulent momentum is transported downward in an
442 orderly manner through turbulent eddies, while at the same height, the turbulent
443 momentum on the right street is transported upward in an orderly manner. There
444 are also differences among different stepped roofs; in most cases, the smaller l_{rs}
445 and the more steps there are, the more orderly the transport of turbulent momen-
446 tum.

447 **5. Summary and Conclusions**

448 This study employed the PALM-LES model to simulate and investigate the
449 turbulence characteristics and airflow impact within different roof street canyon
450 configurations in the urban boundary layer. The analysis focused on mean flow

451 and turbulence properties to comprehensively understand the complexity of tur-
452 bulence within street canyons and its influence on various street canyon layouts.

453 The investigation revealed that the airflow patterns were significantly different
454 between stepped and flat roof configurations. In the flat roof configuration, the
455 airflow patterns in the left and right street canyons were quite similar, with a pri-
456 mary vortex and three secondary vortices. On the other hand, the left street canyon
457 in the stepped roof configuration exhibited two counter-rotating primary vortices,
458 with enhanced vertical motion in the right street. The local velocity statistics in-
459 dicate that the velocity at the pedestrian layer on the left street under the stepped
460 roof is lower than that on the left street under the flat roof, while the situation is
461 exactly the opposite on the right street.

462 In flat roof, high normalized TKE is mainly between $z/H = 1.0$ and $z/H = 1.2$,
463 with a peak above the right windward wall edge. Stepped roof simulations reveal
464 different patterns: high TKE stretches from the left roof side to the first step,
465 while the right side shows lower TKE. The right street canyon consistently ex-
466 hibits higher TKE than the left. Smaller l_{rs} values correlate with higher normal-
467 ized TKE, indicating that more roof steps intensify turbulent momentum and alter
468 airflow dynamics.

469 Although we observed notable differences in vertical and streamwise veloc-

ity disturbances in the right street canyon under the stepped roof configuration compared to the flat roof, such differences were less pronounced in the left street canyon. The third-order moment skewness of streamwise and vertical velocities indicates asymmetry in their respective directions. For flat roofs, streamwise velocity skewness is similar across both streets, showing significant positive fluctuations, while vertical velocity skewness indicates strong downward motion. In contrast, on stepped roofs, streamwise velocity shows weaker positive fluctuations, and vertical velocity exhibits more intense negative skewness, demonstrating that different roof structures significantly affect fluid dynamic characteristics, particularly in the vertical transport of momentum.

As for Reynolds stress, The flat roof displays maximum Reynolds stress at low heights, especially on the left street due to strong downdrafts, unlike the stepped roofs, which show minimal stress. Higher up, between $z/H = 1$ and 1.1 , all roofs exhibit a minimum in Reynolds stress, indicating enhanced downward momentum transport, with stepped roofs showing varied stress levels based on different l_{rs} values.

The absolute value of the dispersive stress on the left street is significantly greater than on the right street, and the larger the l_{rs} , the greater the absolute value of the dispersive stress on the left street. There are significant differences in

489 the contributions and patterns of momentum transfer of dispersive stress between
490 flat and stepped roofs, particularly in the roughness layer. Specifically, dispersive
491 stress contributes more significantly to the total turbulent stress on flat roofs, while
492 its impact is relatively smaller on stepped roofs.

493 The efficiency of turbulence transport indicates that the values are minimized
494 at heights above the obstacle, suggesting effective momentum transfer across the
495 street canyon. For flat roofs, three peaks are evident along the street, with momen-
496 tum being transported upward in an orderly manner at the lower and upper levels,
497 and downward at the mid-level. For stepped roofs, near the ground on the left
498 street, turbulent momentum is orderly propagated downward through turbulent
499 eddies, while at the same height, the right street experiences orderly upward prop-
500 agation of turbulent momentum. Variations also exist among different stepped
501 roofs; generally, the smaller the l_{rs} and the more steps there are, the more orderly
502 the transport of turbulent momentum.

503 Lastly, it is worth noting that the current study provided a preliminary explo-
504 ration of airflow patterns in different stepped roof configurations, considering only
505 neutral stratification. Future research should delve into investigating the influence
506 of density stratification, such as thermal effects, on airflow patterns in stepped
507 roof configurations. Additionally, considering scalar transport in the stepped roof

508 configurations, for instance, pollutant dispersion, could make the research more
509 practically relevant.

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515 **Appendix A. Grid Independence Verification**

516 We conducted a grid independence verification following the approach used
517 by Huang(2022). Figure A.15 presents a comparison among the results obtained
518 using coarse (mesh size = 0.5 m ,384,000 cells), fine (mesh size = 0.333 m,
519 1,296,000 cells), and finer (mesh size = 0.25 m, 3,072,000 cells) meshes. These
520 results are based on the terrain from Simulation 4, which has the highest number
521 of steps. It is observed that the differences among these three mesh resolutions are
522 not significant, especially for the finest mesh, which shows smooth overall results
523 without any abnormal fluctuations. Additionally, a mesh density of 0.25m has
524 reached the limit for the simulation (since the roughness length is 0.1m). Com-
525 bined with the results from wind tunnel measurements discussed in Chapter 3,
526 using a 0.25m mesh resolution for this study is justified.

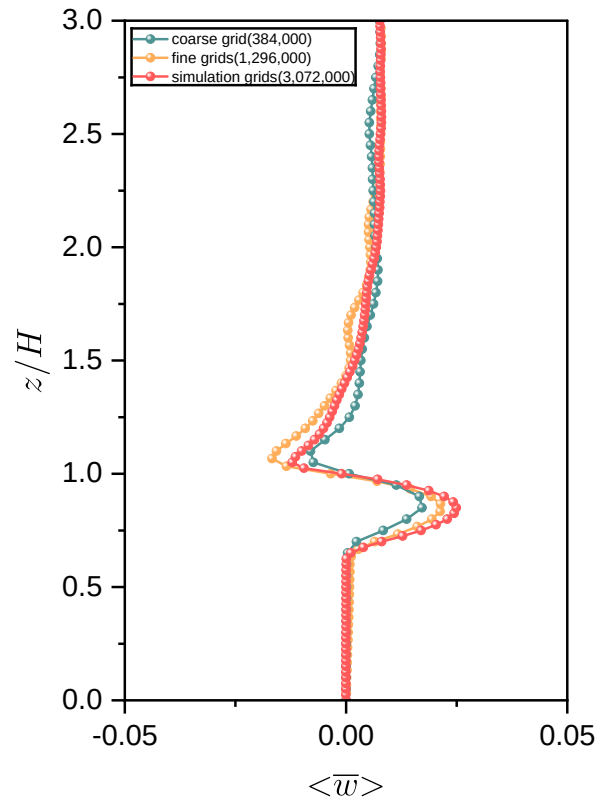


Figure A.15: Verification of grid independence. w represents the spatially and temporally averaged vertical velocity over right street.

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1 Highlights

2 **Investigating the Influence of Stepped Roofs on Wind Dynamics Using Large** 3 **Eddy Simulation**

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- 5 • This study is the first to investigate the impact of stepped roofs on urban
6 airflow with LES.
- 7 • Stepped roofs form unique vortices and enhance vertical airflow more than
8 flat roofs.
- 9 • Turbulence and small-scale motions were higher around stepped roofs and
10 varied with geometry.
- 11 • Wind disturbances in canyons with stepped roofs were tied to changes in
12 roof shape.
- 13 • Significant differences in turbulent momentum transport exist between wind-
14 ward and leeward streets.

Investigating the Influence of Stepped Roofs on Wind Dynamics Using Large Eddy Simulation

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Abstract

This study investigates airflow and turbulence within varying roof configurations in urban boundary layers by using the parallelized large-eddy simulation model(PALM). Key findings reveal stark contrasts in airflow between stepped and flat roof arrangements, with the former presenting dual counter-rotating vortices and enhanced vertical motion in one street, while the latter exhibited a primary vortex and several secondary vortices. Additionally, normalized turbulence kinetic energy(TKE) was markedly lower in flat roof configurations, with stepped roofs fostering more significant turbulence and small-scale turbulent motion. This variability intensified with decreasing step height and quantity. Vertical profiles further disclosed considerable velocity disturbances and larger Reynolds numbers in one street of stepped roofs, affirming the roof's influence on turbulence generation and transport. Dispersive stress also displayed differing characteristics in various canyons. Turbulent momentum transport through eddies significantly dif-

fers between the windward and leeward streets of flat and stepped roofs. Further exploration into density stratification effects and scalar transport in stepped roofs would enhance practical implications.

19 *Keywords:* turbulence, wind force, stepped roof, numerical simulation

20 **1. Introduction**

21 Turbulence, a challenging question prevails ubiquitously in atmospheric phe-
22 nomena (Bourgoin et al., 2020). Characterized by chaotic and irregular fluid mo-
23 tion, turbulence poses numerous challenges in terms of understanding and study
24 (Eames and Flor, 2011). Grasping the concept of turbulence has far-reaching im-
25 plications in diverse fields including fluid physics, environmental fluid dynamics,
26 meteorology, geophysical dynamics, engineering, and astrophysics. Specifically,
27 in meteorology, turbulence serves as a fundamental factor in cloud formation, air-
28 mass mixing, heat and moisture transport in the atmosphere. It impacts boundary-
29 layer processes, aviation safety, and pollutant dispersion. In urban environments
30 or densely populated areas, airflow dictates the environmental conditions for daily
31 activities (Takemi et al., 2020). A trend towards urbanization and growth in urban
32 populations necessitates systematic research on turbulence in urban environments.
33 However, the complexity of city layouts introduces significant challenges to such
34 research (Park et al., 2015). Moreover, local urban scales are often 100 m or

35 smaller, referred to as the microscale or street scale, which complicates detailed
36 simulations (Britter and Hanna., 2013). Street canyons, as fundamental elements
37 in urban environments (Park et al., 2022), warrant special attention owing to their
38 frequent interaction with pedestrian activities. Past research extensively investi-
39 gated turbulence within street canyons via wind tunnel experiments, field obser-
40 vations, and numerical simulations (Letzel et al., 2008; Xie and Castro, 2009;
41 Nakayama et al., 2011; Park et al., 2012; Zhong et al., 2015; Kwak et al., 2016;
42 Duan et al., 2019).

43 Studies have highlighted that an array of factors profoundly influences turbu-
44 lence within street canyons. Key elements characterizing turbulence generation
45 include aspects like urban scale and the ratios of street dimensions (Hang et al.,
46 2009, 2010, 2012), the ratios of frontal and plan areas (Michioka et al., 2014), fluc-
47 tuations in building heights (Nakayama et al., 2011; Chen et al., 2017), disparities
48 in building geometries (Llaguno-Munitxa and Bou-Zeid, 2018), the directionality
49 of wind (Buccolieri et al., 2015) and the thermal effects(Duan and Takemi, 2021;
50 Mouzourides et al., 2022). Moreover, the characteristics and designs of building
51 roofs, particularly variations in their shapes and heights, are increasingly being
52 recognized as significant factors affecting turbulence within these urban environ-
53 ments(Rafailidis, 1997; Dirss et al., 2014; Garau et al., 2018; Chahardoli et al.,

54 2022).

55 The quality of air within street canyons is contingent upon the exchange of
56 air with the overlying atmosphere, a process predominantly dictated by the shear
57 layer generated at the roof level. Consequently, the configuration of the roof
58 emerges as a critical factor influencing the ventilation within the canyon(Garau
59 et al., 2018). To date, considerable advancements have been made regarding the
60 influence of roof shapes on urban turbulence and air pollution. Liu et al.(2020)
61 delved into the analysis of airflow surrounding a single building model with a va-
62 riety of roof shapes. Their findings underscored the crucial role of the roof shape
63 in dictating efficiency, with flat roofs outperforming those with more intricate geo-
64 metrical configurations. Furthermore, they observed that the pedestrian-level flow
65 was markedly impacted by the variations in roof shapes. Chahardoli et al.(2022)
66 found that the vortex size influences particle concentration around buildings de-
67 pending on the building shape. Garau et at.(2018)'s finding indicate that gable
68 roofs often lead to a postponement in the transition from skimming-flow to the
69 wake-interference regime and facilitate the development of a deeper, more turbu-
70 lent roughness layer. The introduction of a gable roof remarkably enhances the
71 momentum flux, particularly in situations of high packing density. The exchange
72 of air is superior compared to buildings with flat roofs, with the advantageous

73 impact being more noticeable for narrower canyons.

74 However, even though previous research has investigated turbulence in obsta-
75 cles configured with various roof shapes(Huang et al.(2009), Takano and Monen
76 (2015)), including Chahardoli et al.(2022)’s work involving numerical simulations
77 of turbulence in obstacles with eight different roof configurations, the majority of
78 simulations tend to focus on flat roofs and gable roofs. Meanwhile, stepped roofs,
79 which are prevalent in real-world scenarios including but not limited to Europe
80 and Asia (see Figure 1), often get overlooked. Considering the aforementioned
81 significance of roof shape on turbulence within street canyons, understanding the
82 impact of stepped roofs on urban turbulence is not only crucial but also carries
83 practical implications.

84 In order to deepen our understanding of the combined impacts of various
85 stepped roofs on turbulent flows within street canyons and the roughness sub-
86 layer, we utilize a Large-Eddy Simulation (LES) modeling approach to compare
87 the turbulence over different stepped roof obstacles with that over flat roof obsta-
88 cles. LES, proven by a number of previous studies (Kanda, 2006; Kanda et al.,
89 2004, 2013; Nakayama et al., 2011; Takemi et al., 2020; Duan et al., 2020, 2022),
90 provides dependable precision in the exploration of urban turbulence and offers
91 flexibility for convenient parameter adjustments.

92 The organization of this study is as follows: Section II provides an overview
93 of the research methodology, including of the employment of a Large-Eddy Sim-
94 ulation (LES) model and the configuration of an urban model, along with in-depth
95 descriptions of the parameters utilized in the LES model. Section III establishes
96 the reliability of the LES model by juxtaposing it with wind tunnel experimental
97 data. Section IV reveals the simulation outcomes, with comprehensive analyses of
98 mean flow, normalized TKE, the normalized mean and turbulence vertical profiles
99 and wind comfort to the left and right street streets. Finally, Section V summarizes
100 the present study by encapsulating the findings from the simulations and offering
101 perspectives on potential avenues for future research.

102 **2. Methodology**

103 *2.1. Numerical model*

104 In this study, the PALM version 6.0(formerly an abbreviation for Parallelized
105 Large-eddy Simulation Model and now an independent name) was adopted for the
106 numerical simulation of turbulent flow and pollutant dispersion in street canyons
107 with different roofs of roughness blocks. As demonstrated in previous research,
108 including obstacle arrays, street canyons, and realistic urban areas, PALM has
109 been broadly used in studies regarding urban flow and pollutant dispersion (Maronga
110 et al. 2020).



(a) An European hotel, © Pixabay GmbH Co., used with permission.



(b) A traditional Chinese house in south of Anhui province © Bin Jiao, used with permission.

Figure 1: Stepped roofs in traditional European and Asian area.

111 The PALM model functions by resolving a set of Navier-Stokes equations
112 with the Boussinesq approximation. Prognostic variables, including velocity com-
113 ponents (u, v, w), passive scalar concentration (s), and subfilter-scale turbulence
114 kinetic energy (TKE), are discretized on an Arakawa C-grid, a staggered grid
115 (Arakawa and Lamb 1977). The magnitudes of velocity, namely u , v , and w , de-
116 note the components in the streamwise, spanwise, and vertical directions, respec-
117 tively. The model applies a third-order Runge-Kutta scheme for time integration,
118 while a fifth-order upwind-biased scheme is used for the discretization of advec-
119 tion terms (Maronga et al. 2015; Letzel et al. 2008).

120 Subgrid-scale (SGS) eddies are parameterized using the 1.5-order TKE scheme
121 for calculating the SGS fluxes of momentum and scalars (Deardorff 1980; Maronga
122 et al. 2015). The model has been verified against multiple field measurements and
123 wind tunnel experiments, revealing a favorable correlation between the simula-
124 tions and the actual measurements (Letzel et al. 2008; Maronga et al. 2013;
125 Yaghoobian et al. 2014; Han et al. 2018).

126 In the paper by Manago et al. 2020, the flow are simulated using large-
127 eddy simulation (LES) and the implicitly filtered non-hydrostatic, incompressible
128 Boussinesq equations, viz.,

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial \tilde{\pi}^*}{\partial x_i} - \frac{\partial}{\partial x_j} \left(\tilde{u}'_i \tilde{u}'_j - \frac{2}{3} \delta_{ij} \tilde{e} \right), \quad (1)$$

where the tilde denotes resolved-scale variables. In this formula, the prime symbol (') represents a derivative, not a deviation from the average value. For the dynamical variables, $\tilde{u}_i = (u, v, w)$ are the velocity components corresponding to the spatial coordinates $x_i = (x, y, z)$, $\tilde{u}'_i \tilde{u}'_j$ is the (subgrid-scale) SGS stress tensor where the double primes denote SGS variables; $\tilde{e} = \frac{1}{2} \tilde{u}'_i \tilde{u}'_i$ is the SGS turbulence kinetic energy (TKE);

$\tilde{\pi}^* = \pi^* + \frac{2}{3} \rho_0 e$ is the modified perturbation pressure (π^*); ρ_0 is the reference density.

2.2. Geometry of roughness obstacle

To effectively and accurately assess how the roofs of obstacles impact airflow within the urban canopy layer and street canyons, a simplified two-dimensional model of a roughness block was devised. This model also facilitates the exploration of turbulent structures within the spanwise direction of street canyons. The computational domain spans 60m in the streamwise direction (x), 20m in the spanwise direction (y), and 40m in the vertical direction (z). The typical obstacle height, denoted as H , is 10 meters. This means that the dimensions of the computational domain are $6H$, $2H$, and $4H$ in the x , y , and z directions, respectively.

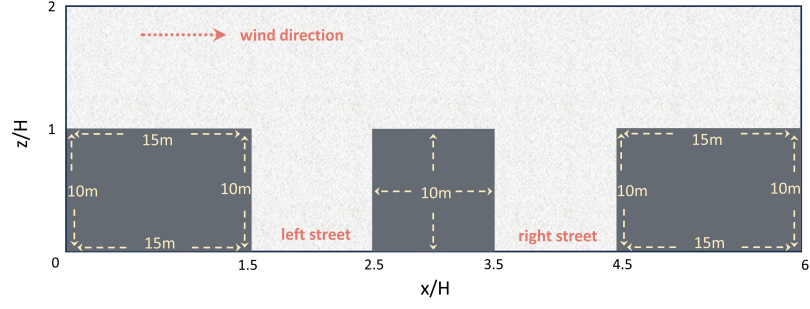
146 Employing a traditional three-dimensional rectangular configuration, the compu-
147 tational grid utilizes a 0.25-meter distance in the Δx , Δy , and Δz directions, thereby
148 constituting a total of 3,072,000 grid cells.

149 To elucidate the influence of different step heights in stepped-roof structures
150 on turbulence, in this context, we employ l_{rs} that represents the ratio of one step
151 height(H_{rs}) to the standard obstacle height:

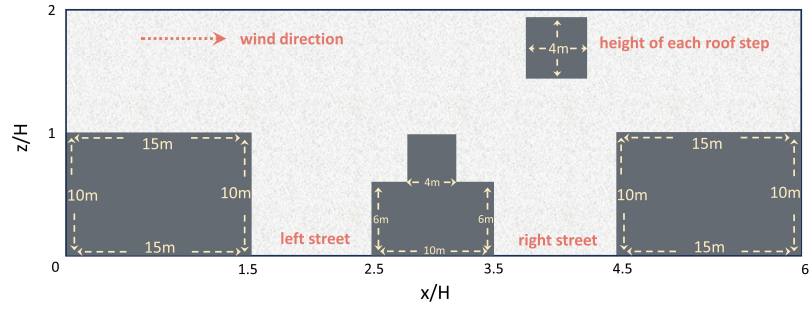
$$l_{rs} = H_{rs}/H. \quad (2)$$

152 Figure 2 presents the configurations of the obstacles utilized in four different
153 simulation experiments. Figure 2a depicts the obstacles with a flat roof having the
154 standard height. Figures 2b, 2c, and 2d, on the other hand, illustrate the obstacles
155 with stepped roofs at varying one roof height. The roof sections in these figures
156 are highlighted in red.

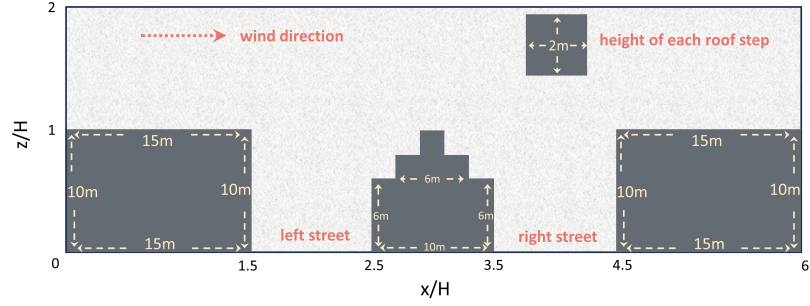
157 This model operates by assuming that the stabilities in the strictly neutral con-
158 ditions. The boundary conditions entail the application of Dirichlet conditions
159 at the left boundary (i.e., the inlet), while the right boundary (i.e., the outlet)
160 adopts radiation boundary conditions. A cyclic condition is applied at the north
161 and south boundaries, or the lateral surfaces. The bottom boundary condition is
162 a no-slip boundary condition, while the top boundary condition is a Neumann



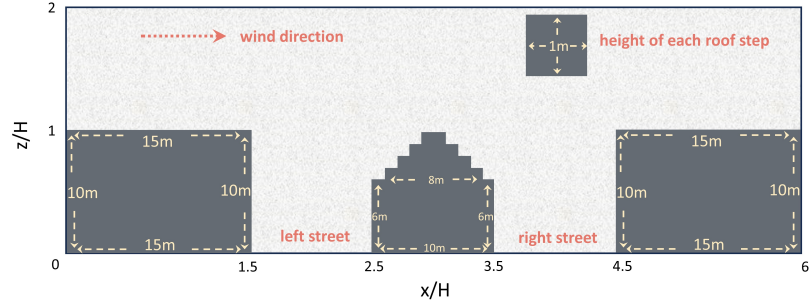
(a) S_1 , flat roof.



(b) S_2 , stepped roof with $l_{rs} = 0.4H$.



(c) S_3 , stepped roof with $l_{rs} = 0.2H$.



(d) S_4 , stepped roof with $l_{rs} = 0.1H$.

Figure 2: The distribution of obstacles for four different roofs.

163 boundary condition. The boundary conditions close to the wall are defined using
164 parameters derived from the Monin-Obukhov similarity theory instead of using a
165 standard wall function. These parameters include a roughness length of $z_0 = 0.1m$
166 and a layer of constant flux that extends from the wall to the first point on the grid.

167 In the simulation, a turbulent inflow technique is employed , which involves
168 the recirculation of turbulent flow from the primary outlet back to the inlet. Specif-
169 ically, similar to the approach of Nakayama et al., 2011, we recycled the wind
170 profile of the airflow passing through obstacles in a precursor run to obtain a more
171 realistic inflow wind profile. The recycling technique initially proposed by Lund
172 et al.(1998) and further refined by Kataoka and Mizuno (2002). This recycling
173 procedure is layered onto the velocity profile created by the precursor flow, which
174 assists in reaching statistical equilibrium and fosters the development of adequate
175 turbulence. The recycling plane is located near the outlet.

176 The precursor run lasts for a duration of 5 hours and employs periodic bound-
177 aries, and is driven by an external pressure gradient having the magnitude $dp/dx =$
178 $-6 \times 10^{-4} \text{ Pa m}^{-1}$. The prevailing speed U_f is about 1.36 m s^{-1} and the Reynolds
179 number $Re (= U_f H / \nu)$ is about 1.12×10^6 . The total simulation time is 4800 sec-
180 onds, which includes an initial 1800-second spin-up period to stabilize the flow
181 field physically and ensure the precision of the simulation results. The data collec-

tion involves sampling every 6 seconds over a period of 3000 seconds, and these data are then used for subsequent analysis. We conducted a time series analysis on the data spanning 3000 seconds, demonstrating the complete development of turbulence and attainment of statistical equilibrium (figure omitted).

Figure 3 presents the Fourier spectrum and wavelet spectrum of vertical fluctuations. Within the dashed box, although the Fourier spectrum shows some oscillations, the wavelet spectrum is relatively smooth. Both spectra closely follow the "-5/3" power law. Specifically, in this interval, the least squares fit of the Fourier spectrum is -1.68, and the wavelet spectrum is -1.74, both of which are very close to the theoretical value of -1.67. Furthermore, this interval clearly falls within the inertial subrange predicted by Kolmogorov (10^{-3} to 10^3), providing further evidence of achieving turbulence equilibrium.

Table 1 provides an inclusive summary of the parameters and the urban-like geometry for easy reference.

In the notation used within the paper, $\langle \rangle$ denotes spatial averaging, which includes both spanwise and streamwise directions, $(\overline{})$ represents time averaging, and $(')$ signifies the deviation from the average value.

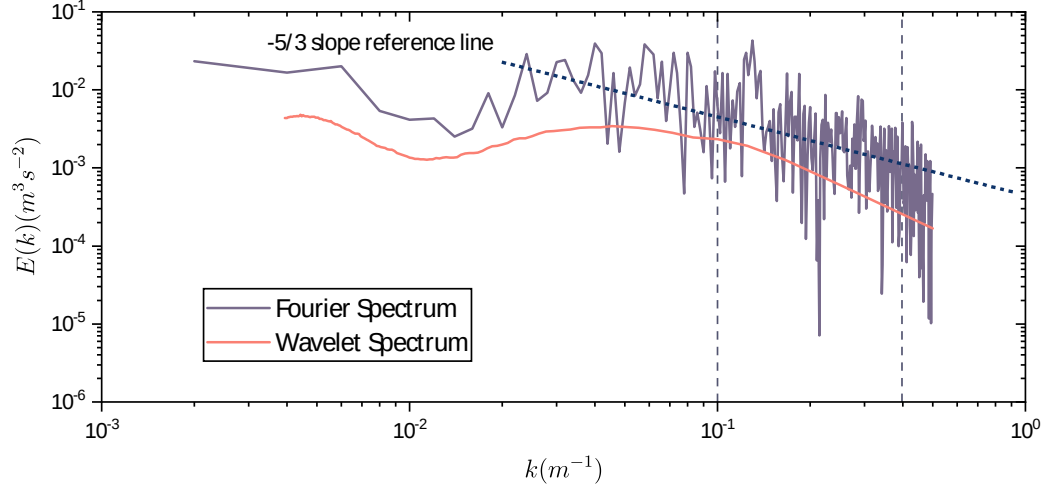


Figure 3: Energy spectrum of vertical fluctuation velocity $x/h=2$, $y/h=0.5$, $z/H=0.5$.

Table 1: Domain dimensions			
Parameter	Attribute	Set-up	Unit
H_N	Normal obstacle height	10	m
H_{rs}	one step height	1/2/4	m
L_x	Domain size in the x -direction	60	m
L_y	Domain size in the y -direction	20	m
L_z	Domain size in the z -direction	40	m
Δx	Gird size in the x -direction	0.25	m
Δy	Gird size in the y -direction	0.25	m
Δz	Gird size in the z -direction	0.25	m
$L_x/\Delta x$	Number of grids in the x -direction	240	number
$L_y/\Delta y$	Number of grids in the y -direction	80	number
$L_z/\Delta z$	Number of grids in the z -direction	160	number
σ_{grids}	Number of grids	3,072,000	number
z_0	Roughness length	0.1	m

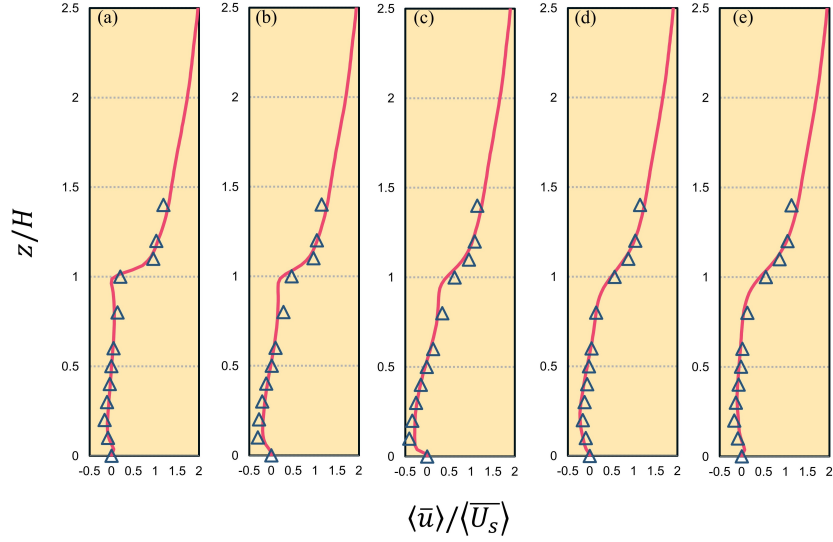


Figure 4: Normalised mean streamwise velocity profiles from the simulation results (red solid curve) and wind tunnel measurement results (blue hollow triangle). $\langle \bar{U}_s \rangle$ represents the stream-wise velocity averaged over the shear layer ($1 \leq z/H \leq 1.5$, about 0.8 m s^{-1}), and a, b, c, d, e are located at $3.6H$, $3.75H$, $4.0H$, $4.25H$, and $4.4H$, respectively.

3. Validation

While numerous studies have established the precision of the PALM model in replicating urban turbulence, juxtaposing these simulation outcomes with data from wind-tunnel measurements remains essential for affirming the trustworthiness of the present simulations.

Simulation measurement No. 1 (S_1) was deliberately chosen for correlation with wind tunnel measurements by employing an identical normalized obstacle height set-up. Figure 4 illustrates the comparison between the LES simulation findings and the wind tunnel data collected from a previous research (Brown

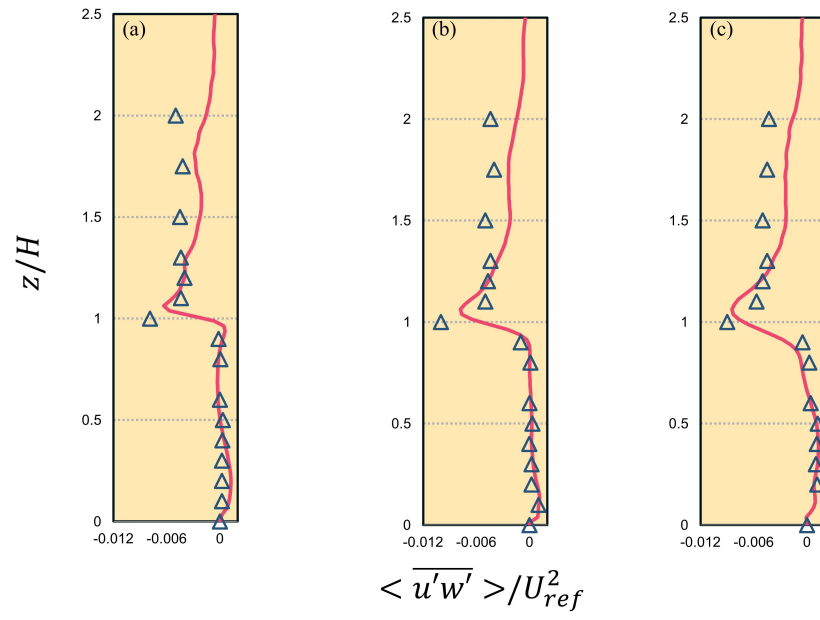


Figure 5: Normalised Mean Reynolds stress velocity profiles from the simulation results (red solid curve) and wind tunnel measurement results (blue hollow triangle) at $3.75H$, $4.0H$, $4.25H$.

208 2000). To verify the credibility of the LES model, vertical profiles of normalized
209 streamwise wind speed were utilized at various characteristic points within the
210 street canyon.

211 The LES findings demonstrate a promising concordance with the wind tun-
212 nel experiment results at five separate points in the streamwise direction, namely,
213 $3.6H$, $3.75H$, $4.0H$, $4.25H$, and $4.4H$. Among these comparisons, the LES out-
214 comes for $3.75H$ and $4.0H$ near the ground are slightly undervalued, aligning with
215 the findings of Duan and Ngan (2018). This minor discrepancy is ascribed to the
216 roughness length set at $0.1m$ (see Table 1), representing a highly rough surface in
217 contrast to the surfaces in the wind-tunnel measurements.

218 To ensure the accuracy of our simulation in terms of turbulence momentum, In
219 Fig. 5, we also compared the Reynolds stress results with the wind tunnel results
220 from Michioka et al.(2011). Although the setup of our simulation is not entirely
221 identical to the wind tunnel simulations(In the Michioka’s study, the inflow was
222 set over open ground, whereas in this simulation, the inflow was obstructed by an
223 obstacle.), and there are some minor discrepancies in peak values, the overall re-
224 sults were favorable, and the trends were generally consistent. This demonstrates
225 the success of our simulation in replicating turbulence statistics.

226 Taken as a whole, the outcomes derived from the current LES model properly

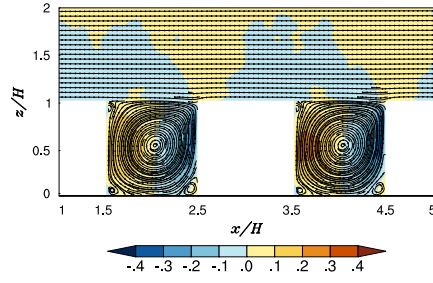
227 depict the fundamental state of the actual flow field and are deemed accurate and
228 trustworthy. Hence, the residual three simulation results can also be utilized to
229 study turbulent flow patterns in varying roof configurations.

230 **4. Numerical Results**

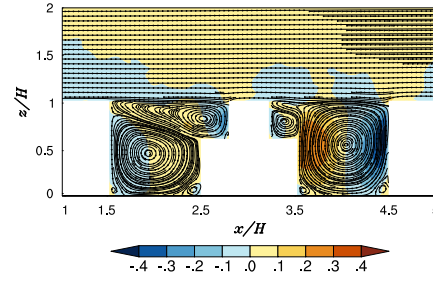
231 *4.1. Mean flow and velocity statistics*

232 This section will present the results for mean flow and velocity statistics. Here,
233 the mean flow represents the most fundamental and typical characteristics of the
234 flow field over a specific period.

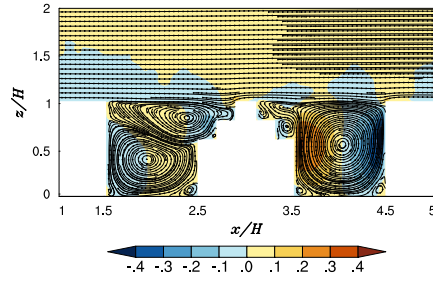
235 Firstly, Figure 6 illustrates the time-averaged flow pattern. The results shown
236 in Fig. 6a (S_1) have been confirmed in multiple studies, demonstrating the pres-
237 ence of a prominent primary vortex within the street canyon, along with three
238 smaller vortices near the corners and the obstacle height of the leeward wall. A
239 characteristic skimming flow pattern emerges, with the air predominantly flowing
240 over the obstacle tops and scarcely penetrating into the canyon interior. Stream-
241 lines above the obstacle tops exhibit a pattern akin to uniform lines. The average
242 vertical speed within the street canyon shows an approximately symmetric struc-
243 ture, with comparable velocity magnitudes on either side of the canyon centerline.
244 The vertical velocity near the leeward wall is upward, while that near the wind-
245 ward wall is downward. The basic flow form of the air on the left and right streets



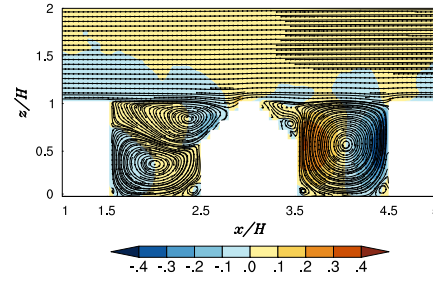
(a) S_1 , flat roof.



(b) S_2 , stepped roof with $l_{rs} = 0.4H$.



(c) S_3 , stepped roof with $l_{rs} = 0.2H$.



(d) S_4 , stepped roof with $l_{rs} = 0.1H$.

Figure 6: Spanwise and temporally averaged mean flow for the case of (a) S_1 , (b) S_2 , (c) S_3 and (d) S_4 . Arrows indicate streamlines and color shadings denote the magnitude of time-averaged vertical velocity (contours, unit: $m s^{-1}$) in the $x-z$ plane.

246 are similar, although the vertical movement of the airflow in the right street is
247 slightly greater than that in the left street.

248 The remaining three results contrast significantly with those from S_1 , primarily
249 seen in the completely different flow patterns on the left and right sides of the
250 street. The most notable difference is the appearance of two primary vortices in
251 the left side of the street canyon, along with a weakening of vertical motion. The
252 larger primary vortex below is counter-clockwise, while the primary vortex in S_1 is
253 clockwise. This indicates that in the left street canyon with flat roofs and stepped
254 roofs, the stark contrast in flow direction has a potent impact on momentum and
255 scalar transport within the street canyon. Meanwhile, in the right street canyon,
256 compared to S_1 , the vertical movement of the airflow has notably strengthened.
257 Additionally, a secondary vortex forms at the top left corner, near the stepped
258 roof, varying according to different roof shapes.

259 The results from S_2 , S_3 , and S_4 are generally similar, but they show minor
260 variations according to the differences in l_{rs} . As l_{rs} decreases, the vortex in the
261 left bottom corner above the left street becomes larger, and the extreme value areas
262 of vertical motion on the right side also grow. Specific numerical values can be
263 found in Fig. 7, which will be described later.

264 Figure 7 illustrates the specific magnitudes of updrafts and downdrafts on both

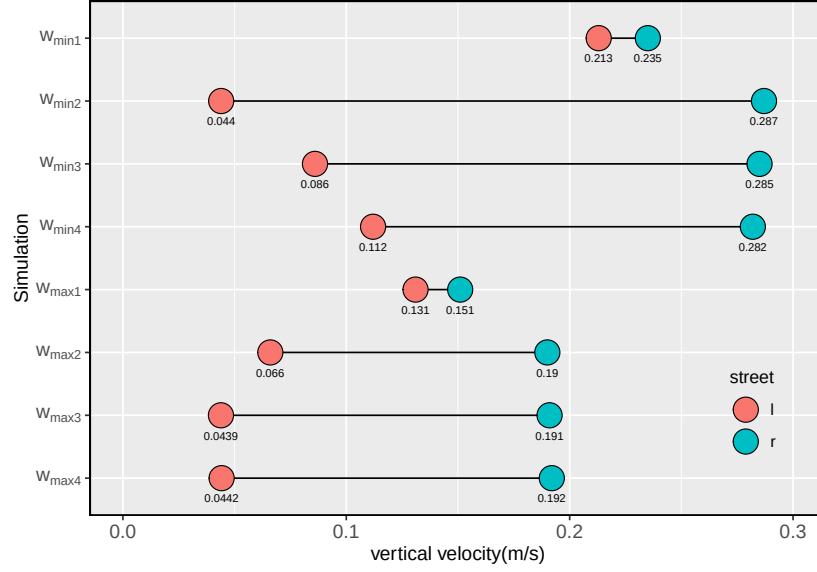


Figure 7: Maximum absolute values of time- and spanwise-averaged vertical velocity below the obstacle height in four different simulations, where vertical velocity w_{max} is positive and w_{min} is negative(unit: $m s^{-1}$).

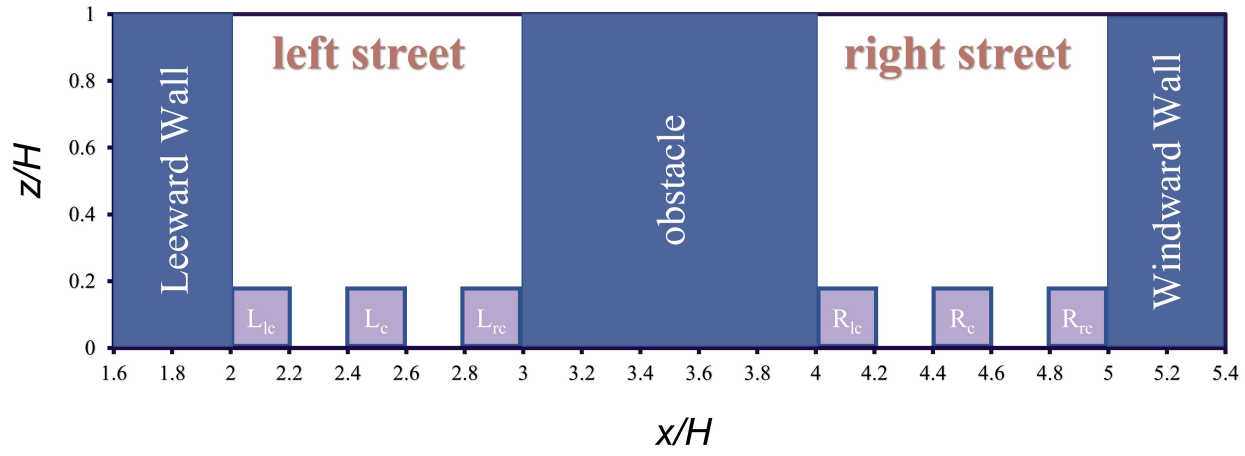
265 sides of the street in four simulations. From the length of the lines connecting the
 266 red and green balls, we can clearly see that in the flat-roof scenario, the differ-
 267 ence in updrafts and downdrafts between the two sides is minimal. However, in
 268 the stepped-roof configurations, different values of l_{rs} exhibit distinct behaviors.
 269 The smaller the l_{rs} , the greater the downdraft movement on the left side of the
 270 street and the smaller it is on the right side, reducing the disparity in downdraft
 271 movements between the two sides. Regarding the updrafts, the smaller the l_{rs} , the
 272 smaller the updraft on the left side and the greater the downdraft on the right side,
 273 increasing the disparity in downdraft movements between the two sides, though

274 the results for S_3 and S_4 are relatively similar.

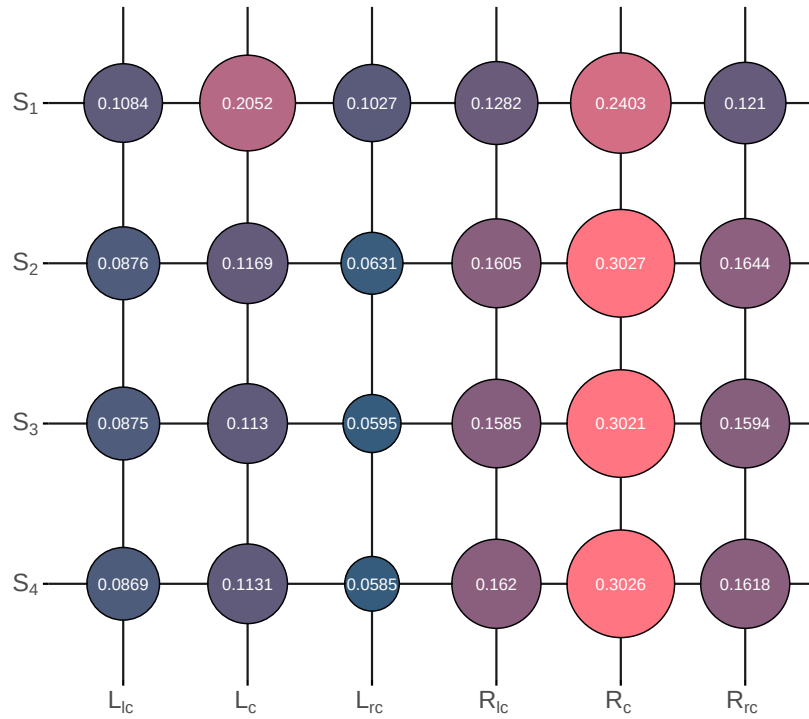
275 In addition to the vertical velocity on the streets with different roof types, we
276 also calculated the local average velocity($V = \sqrt{u^2 + v^2 + w^2}$) at the pedestrian
277 layer to explore the impact of different roof configurations on local average ve-
278 locity(Fig. 8). Specifically, we selected the left corner, center, and right corner
279 of each street at a pedestrian layer height of 1.75m as the points for statistical
280 analysis. On the left street, the average velocity under flat roofs was consistently
281 higher than that under stepped roofs, whereas on the right street, the situation was
282 reversed. Under flat roofs, the average velocity at the same locations on the left
283 and right streets showed little difference, but under stepped roofs, the differences
284 were significant, reaching 2 to 3 times. For stepped roofs, on the left street, the
285 smaller the l_{rs} , the lower the average velocity at both corners and the higher the
286 average velocity in the center, while on the right street, the differences in average
287 velocity were not significant.

288 4.2. *Turbulence statistics*

289 In this section, we discuss the turbulence statistics including the normalized
290 turbulent kinetic energy (TKE), the turbulence intensities and the skewness of the
291 u and w velocity components. The normalized TKE indicate the evolution of
292 turbulence within that time span. The TKE is defined as $TKE = \frac{1}{2}(u'^2 + v'^2 +$



(a) Six statistical areas, each area has a length of $0.2H$ and a height of $0.175H$.



(b) The spatially and temporally averaged velocity(unit: $m s^{-1}$).

Figure 8: The spatially and temporally averaged velocity at six statistical locations in the four simulations are reported. These locations are specifically positioned at the left corner, center, and right corner on both the left and right sides of the street. Each area has a length of $0.2H$ and a height of $0.175H$, representing an approximate pedestrian layer height of 1.75 meters.

293 $w'^2)$, where u' , v' and w' indicate deviations from the time-averaged measures
 294 of the velocity components in the streamwise (u), spanwise (v), and vertical (w)
 295 directions, respectively.

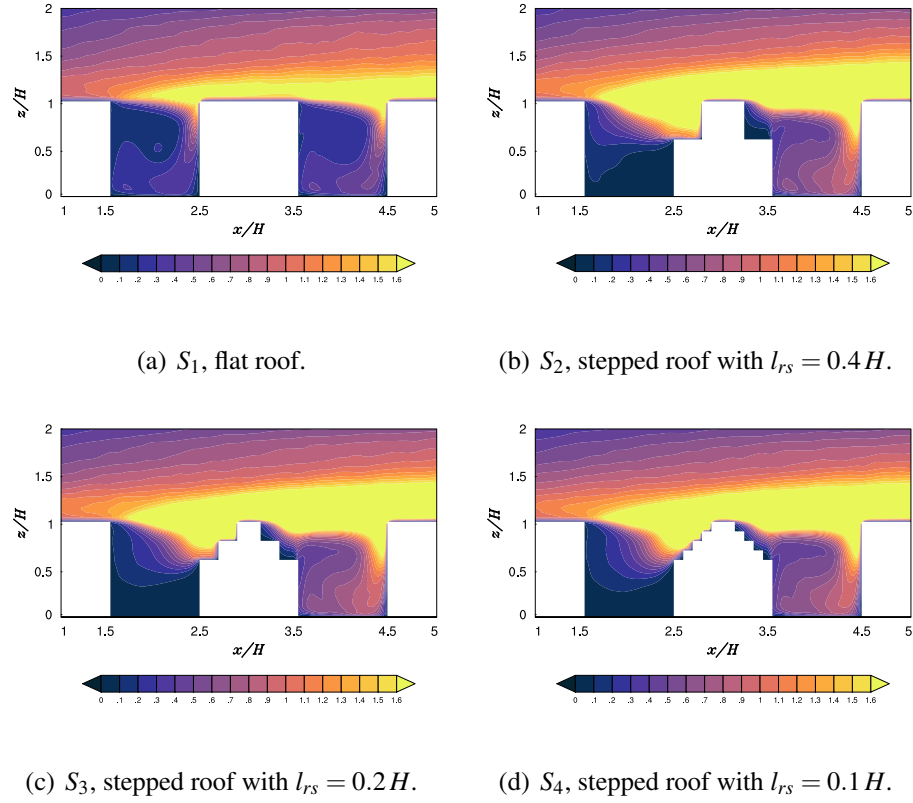


Figure 9: Normalised spanwise and temporally averaged turbulent kinetic energy($\langle \overline{TKE} \rangle / U_{ref}^2$) for (a) S_1 , (b) S_2 , (c) S_3 and (d) S_4 . The numerical values have been amplified by a factor of 100.

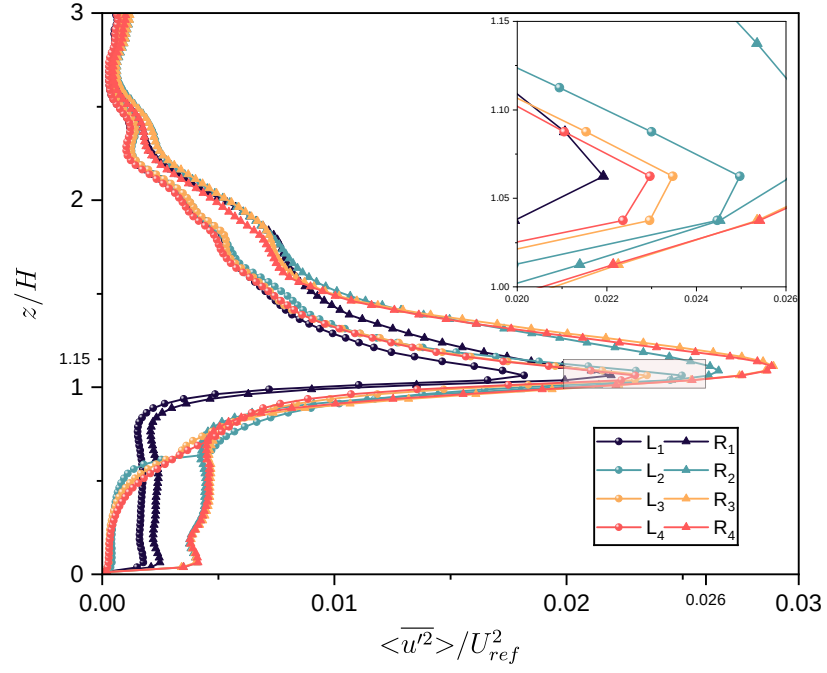
296 Figure 9 represents the normalized TKE in the four simulations. Starting with
 297 Fig. 8a (S_1), the area of high normalized TKE primarily lies between $z/H = 1.0$
 298 and $z/H = 1.2$, slightly lower at the edges of the two windward walls. Above

299 the edge of the windward wall on the right side of the street, there is a region
300 of maximum value. Similar to previous simulations, in the street canyon, the
301 normalized TKE exhibits a vortex-like appearance.

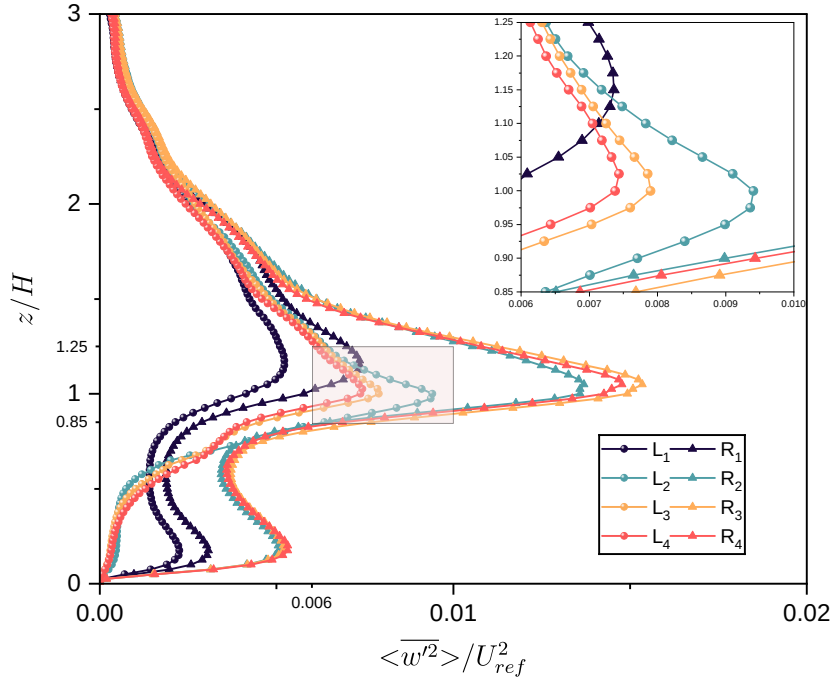
302 The simulation with the stepped roof shows a different behavior: the high-
303 value region of normalized TKE extends from the left side of the roof up to the
304 height of the first step, while the right side of the roof exhibits a low TKE re-
305 gion, especially close to the roof. Observing the TKE in the left and right street
306 canyons, the TKE in the right street canyon is significantly higher than that in the
307 left street canyon. The simulation results for the three stepped roofs are similar,
308 but according to quantitative analysis, the smaller the l_{rs} , the greater the normal-
309 ized TKE. This suggests that an increase in the number of roof steps leads to more
310 turbulent momentum generation, thereby affecting the airflow movement.

311 Overall, the simulation results for the flat roof have generally smaller normal-
312 ized TKE. For the stepped roof, as l_{rs} decreases, the maximum value area of the
313 normalized TKE gets larger, and the maximum values also increase.

314 Figure 10 indicates the vertical profiles of the mean variance of the normalised
315 streamwise velocity(Fig. 9a) and vertical velocity(Fig .9b) over the left(L) or right
316 street(R). These are averaged spatially(In the streamwise direction,1.5H-2.5H for
317 the L, and 3.5H-4.5H for R.) at each height and over time for different roofs. The



(a) Variance of streamwise velocity.



(b) Variance of vertical velocity.

Figure 10: Vertical profiles of temporally averaged, and spatially averaged variance of (a) streamwise velocity, (b) vertical velocity. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

318 numbers in the subscript of the data labels in the figure represent the number of
319 the simulation, and "L" and "R" represent the left street or the right street, respec-
320 tively. For example, " R_2 " represents the simulation results of the right street in the
321 second simulation. Note that the areas within obstacles are not included in this
322 computation. For clarity, the notation used in the following sections corresponds
323 to the specific street canyon each simulation is targeting.

324 Let's first discuss variance of streamwise velocity(Fig. 10a). In the S_1 , which
325 refers to the flat roof, the variance of the streamwise velocity for both the left and
326 right streets is noticeably smaller than in the remaining three sets, which corre-
327 spond to the stepped roof results. Furthermore, the peak values for the flat-roof
328 model are slightly lower than those for the stepped roof model. As for S_2 , S_3 , and
329 S_4 , the left and right streets demonstrate completely different outcomes. As l_{rs}
330 decreases, the peak of the variance of the streamwise velocity on the left street de-
331 creases, whereas the peak of the variance of the streamwise velocity on the right
332 street increases. When the height is lower than $z/H = 0.8$, the variance of the
333 streamwise velocity on the right street is noticeably larger than on the left street.

334 We now examine the variance of the vertical velocity(Fig. 10b). Contrary to
335 the findings concerning the variance of the streamwise velocity, the variabilities
336 of the vertical velocity show a pronounced discrepancy between the left and right

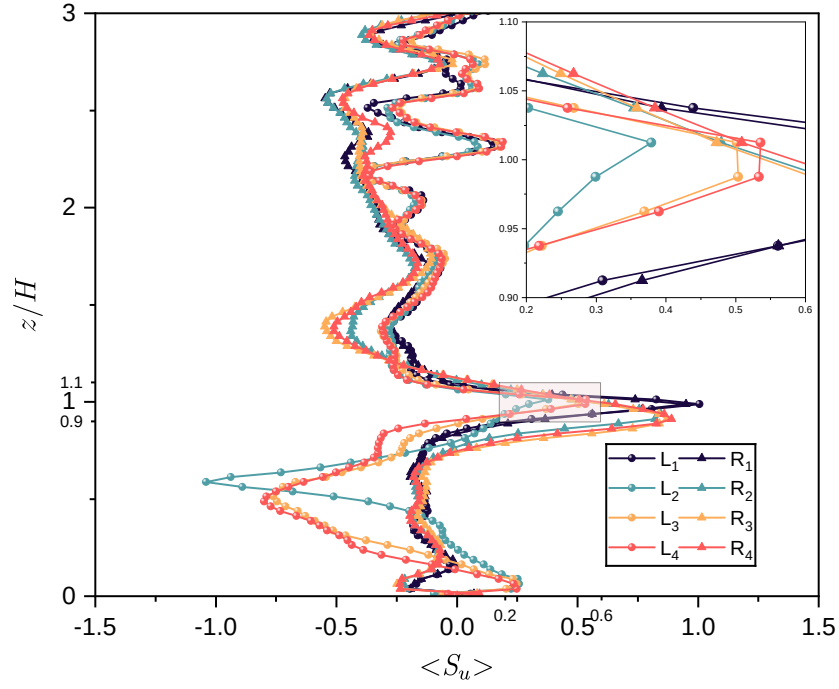
337 streets. From the results of S_1 , the peak of the variabilities of the vertical velocity
338 is smaller in the left street, hovering around 0.004, whereas it's notably higher in
339 the right street, approximating 0.008.

340 In the case of the stepped roof configurations, the difference between the left
341 and right streets is starkly pronounced. The left street's peak hovers around 0.07-
342 0.09, whereas the right street's peak ranges between 0.014 and 0.016 about two
343 to three times that of the left street. As l_{rs} decreases, the variance of the vertical
344 velocity increases on the left street, while in the right street, the results of S_2 are
345 smaller than those of S_3 and S_4 .

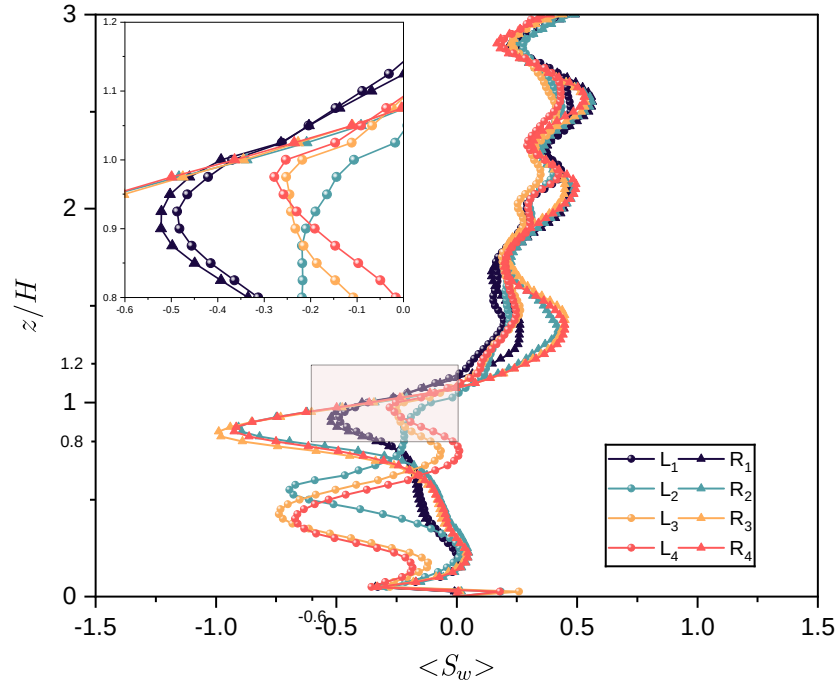
346 In Fig. 11, we discuss the third-order moment skewness of the streamwise
347 velocity($S_u = \overline{u'^3} / \sqrt{(\overline{u'^2})^3}$) and the vertical velocity($S_w = \overline{w'^3} / \sqrt{(\overline{w'^2})^3}$) in order
348 to understand the asymmetry of the streamwise velocity in the streamwise direc-
349 tion and the vertical velocity in the vertical direction.

350 For skewness of the streamwise velocity, specifically, large positive absolute
351 values indicate the presence of extremely high positive horizontal velocities over
352 short periods, while large negative absolute values indicate extremely high nega-
353 tive horizontal velocities over short periods. Our main focus is on variations near
354 and below the building height.

355 Around $z/H=1.0$, the peak values for both stepped and flat roofs occur at this



(a) Skewness of streamwise velocity.



(b) Skewness of vertical velocity.

Figure 11: Vertical profiles of temporally averaged, and spatially averaged skewness of (a) streamwise velocity, (b) vertical velocity. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

356 height. For flat roofs, this represents a typical skimming flow. The peak values
357 for both the left and right streets are close and greater than those for the stepped
358 roofs. The S_u on the right side of the stepped roofs is significantly higher than on
359 the left side, and the peak increases with larger l_{rs} .

360 At $z/H=0.6$, which is the height of the edge of the stepped roofs, all stepped
361 roofs exhibit a trough in S_u on the left street, with S_2 having the lowest value. At
362 this height, there are instances of airflow moving rapidly towards the leeward side.

363 At near-ground heights, the right street of the stepped roofs exhibits values
364 opposite to those of the left street and the flat roofs, indicating that the stepped
365 roofs significantly impact the airflow at the bottom of the left street.

366 For the skewness of vertical velocity, large positive absolute values indicate
367 the presence of extremely high vertical motions over short periods, while large
368 negative absolute values indicate extremely high downward motions over short
369 periods.

370 At $z/H=0.8$ to 0.9 , there is a trough for both the stepped and flat roofs on the
371 right street, with the flat roof's values significantly lower than those of the stepped
372 roofs.

373 At $z/H=0.3$ to 0.6 , the flat roof's results are close to zero on the left street,
374 while the stepped roofs exhibit a trough. The trough for S_2 is slightly higher than

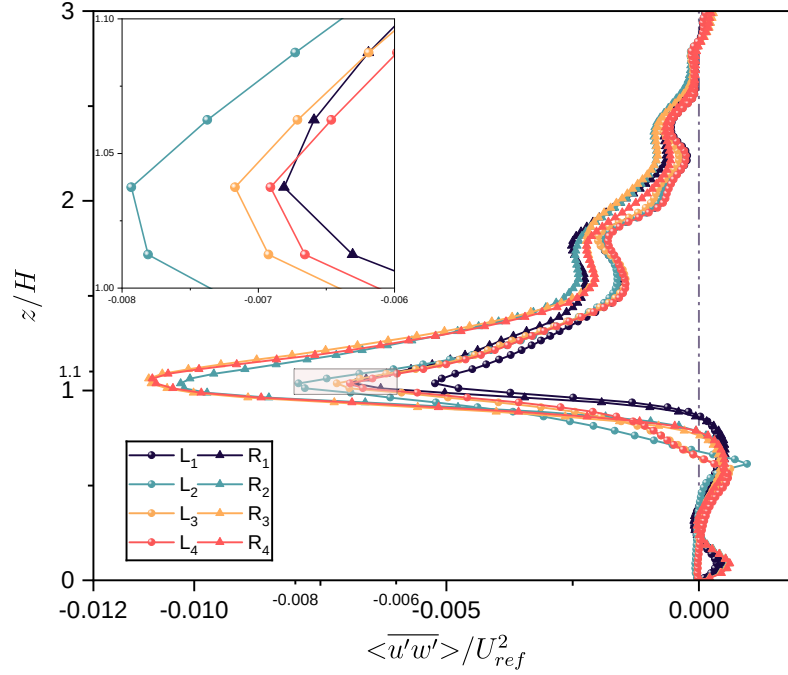


Figure 12: Vertical profiles of normalised, temporal, and spatially averaged Reynolds stress. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

those for S_3 and S_4 .

Near the ground and above $z/H=1.2$, all results show consistency. This indicates that stepped roofs impact vertical airflow in the mid-to-upper layers of the street canyon, causing more short-term but significant downward motions.

4.3. Turbulence momentum transport

Then we examined the turbulence characteristics in terms of turbulent stresses.

In Fig. 12, the vertical profiles of the mean Reynolds stress averaged horizontally

382 and temporally are shown for different roofs.

383 The Reynolds stress can be considered in two parts. At a relatively low height
384 (below $z/H = 0.1$), the results of the flat roof (S_1) show a maximum value on the
385 left street, about 0.001, whereas the Reynolds stress of the stepped roofs (S_2 , S_3 ,
386 S_4) consistently approach zero. A possible reason is that on flat roofs, airflow is
387 more likely to separate at the edges and form strong downdrafts above the street,
388 a process less pronounced with stepped roofs. This leads to stronger vertical air-
389 flows in street canyons (which is also evident in Figure 5), resulting in higher
390 Reynolds stress at the bottom of the left-side street canyon. On the right street,
391 the maximum value of S_1 is approximately 0.001, while the Reynolds stress of the
392 stepped roofs is litter higher than that of the flat roof. Near $z/h = 0.6$, all results
393 show a minor peak, among them, the results for S_2 (where l_{rs} is the largest) are
394 significantly the highest.

395 For higher elevations (between $z/H=1$ to 1.1), the Reynolds stress in all the
396 simulations presents a consistent minimum, demonstrating an enhancement in
397 the downward transport of momentum at this location. The absolute values of
398 Reynolds stress for the flat roof (S_1) on both the left and right streets are notice-
399 ably lower than those for the other stepped roof results. Similarly, as l_{rs} decreases,
400 the absolute value of Reynolds stress on the left street becomes smaller, whereas

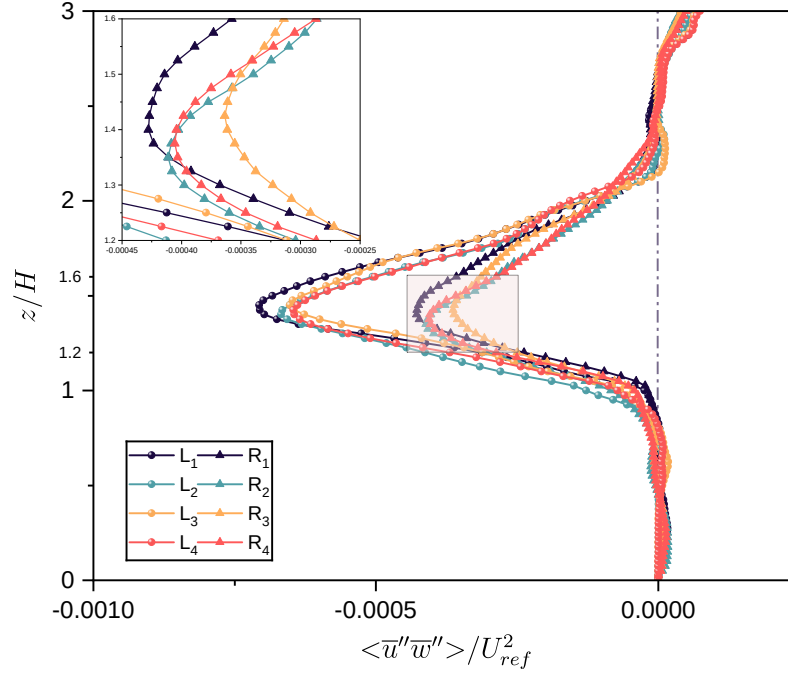


Figure 13: Vertical profiles of normalised, temporal, and spatially averaged dispersive stress. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

401 the absolute value on the right street becomes larger, however, the results for S_3
402 and S_4 are quite similar. This is consistent with the results for the variance of the
403 streamwise velocity and the variance of the vertical velocity. Overall, near this
404 height, the stepped roofs promote the downward transport of momentum, and dif-
405 ferent l_{rs} values affect the Reynolds stress of the left and right streets differently.

406 Dispersive stress refers to the stress in a fluid flow caused by spatial variations

407 in flow velocity, which is often overlooked in urban canopy studies, plays a signif-
408 icant role in turbulent transport. It has, however, attracted attention in recent stud-
409 ies (San tiago and Martilli, 2010; Giometto, 2016; Yoshida and Takemi, 2018).
410 When dispersive fluxes exhibit positive values, a countergradient flux, which sig-
411 nifies the downward transport of low momentum or the upward transport of high
412 momentum (Nazarian et al., 2020).

413 In Fig. 13. Overall, both the flat and stepped roofs show similar trends in the
414 variation of dispersive stress along the left and right streets, with a peak at a height
415 of $z/H = 1.3$ to 1.4 . However, the absolute value of the dispersive stress on the
416 left street is significantly greater than that on the right. This indicates that at this
417 height, all results show a pattern of low momentum being transported upwards
418 and high momentum being transported downwards, with the phenomenon being
419 more pronounced on the left street. Comparing the results for the three different
420 types of stepped roofs, on the left street, the larger the l_{rs} , the greater the absolute
421 value of the dispersive stress.

422 If we compare the results of Reynolds stress and dispersive stress between
423 stepped and flat roofs, we find that in the roughness layer, although the Reynolds
424 stress is lower for flat roofs, the dispersive stress is higher. This indicates that
425 in flat roofs, dispersive stress contributes more significantly to the total turbulent

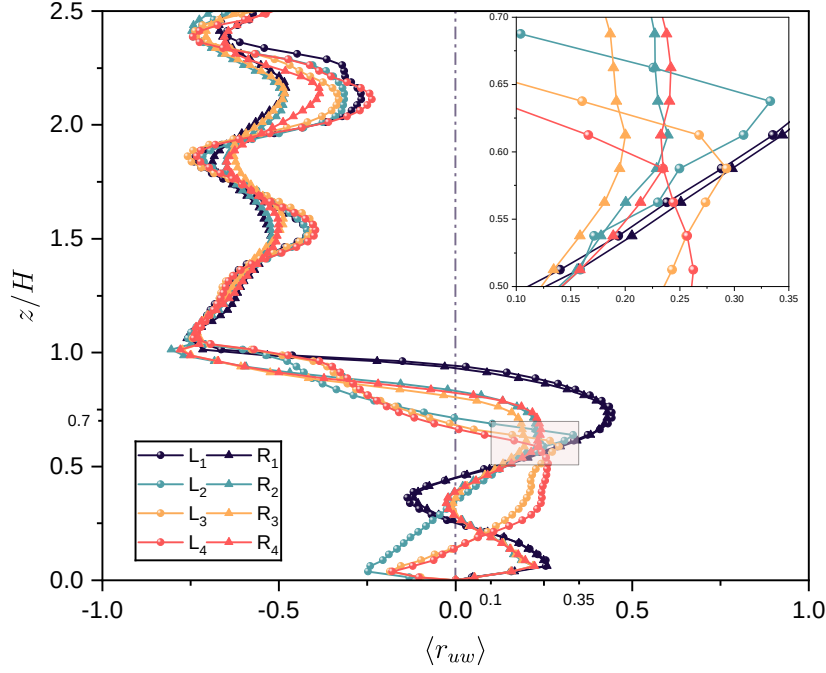


Figure 14: Vertical profiles of temporal, and spatially averaged turbulent transport efficiency. The same color represents simulations with the same simulation, and the triangles indicate left streets and circles indicate right streets.

stress, whereas in stepped roofs, the contribution of dispersive stress to turbulent stress is smaller.

To better clarify the relationship between turbulent momentum and turbulent eddies, we have also analyzed the efficiency of turbulence transport($r_{uw} = \overline{u'w'}/\sigma_u\sigma_w$) in Fig. 14. The further the value of r_{uw} deviates from zero, the more organized the turbulence, with momentum being transported upward or downward

432 in an orderly manner through turbulent eddies. All results show minimal values
433 at heights above the obstacle, which is a very typical phenomenon in the urban
434 canopy layer, indicating highly effective momentum transfer. The main differ-
435 ences occur within the street canyons:

436 For flat roofs, the r_{uw} results are similar on both the left and right streets, show-
437 ing three peaks at heights of $z/H = 0.1$, $z/H = 0.4$, and $z/H = 0.8$. Momentum
438 is transported upwards in an orderly fashion at the lower and upper levels, while
439 it is transported downwards in an orderly fashion at the middle level.

440 The results for stepped roofs differ significantly from those of flat roofs. Near
441 the ground on the left street, turbulent momentum is transported downward in an
442 orderly manner through turbulent eddies, while at the same height, the turbulent
443 momentum on the right street is transported upward in an orderly manner. There
444 are also differences among different stepped roofs; in most cases, the smaller l_{rs}
445 and the more steps there are, the more orderly the transport of turbulent momen-
446 tum.

447 **5. Summary and Conclusions**

448 This study employed the PALM-LES model to simulate and investigate the
449 turbulence characteristics and airflow impact within different roof street canyon
450 configurations in the urban boundary layer. The analysis focused on mean flow

451 and turbulence properties to comprehensively understand the complexity of tur-
452 bulence within street canyons and its influence on various street canyon layouts.

453 The investigation revealed that the airflow patterns were significantly different
454 between stepped and flat roof configurations. In the flat roof configuration, the
455 airflow patterns in the left and right street canyons were quite similar, with a pri-
456 mary vortex and three secondary vortices. On the other hand, the left street canyon
457 in the stepped roof configuration exhibited two counter-rotating primary vortices,
458 with enhanced vertical motion in the right street. The local velocity statistics in-
459 dicate that the velocity at the pedestrian layer on the left street under the stepped
460 roof is lower than that on the left street under the flat roof, while the situation is
461 exactly the opposite on the right street.

462 In flat roof, high normalized TKE is mainly between $z/H = 1.0$ and $z/H = 1.2$,
463 with a peak above the right windward wall edge. Stepped roof simulations reveal
464 different patterns: high TKE stretches from the left roof side to the first step,
465 while the right side shows lower TKE. The right street canyon consistently ex-
466 hibits higher TKE than the left. Smaller l_{rs} values correlate with higher normal-
467 ized TKE, indicating that more roof steps intensify turbulent momentum and alter
468 airflow dynamics.

469 Although we observed notable differences in vertical and streamwise veloc-

ity disturbances in the right street canyon under the stepped roof configuration compared to the flat roof, such differences were less pronounced in the left street canyon. The third-order moment skewness of streamwise and vertical velocities indicates asymmetry in their respective directions. For flat roofs, streamwise velocity skewness is similar across both streets, showing significant positive fluctuations, while vertical velocity skewness indicates strong downward motion. In contrast, on stepped roofs, streamwise velocity shows weaker positive fluctuations, and vertical velocity exhibits more intense negative skewness, demonstrating that different roof structures significantly affect fluid dynamic characteristics, particularly in the vertical transport of momentum.

As for Reynolds stress, The flat roof displays maximum Reynolds stress at low heights, especially on the left street due to strong downdrafts, unlike the stepped roofs, which show minimal stress. Higher up, between $z/H = 1$ and 1.1 , all roofs exhibit a minimum in Reynolds stress, indicating enhanced downward momentum transport, with stepped roofs showing varied stress levels based on different l_{rs} values.

The absolute value of the dispersive stress on the left street is significantly greater than on the right street, and the larger the l_{rs} , the greater the absolute value of the dispersive stress on the left street. There are significant differences in

489 the contributions and patterns of momentum transfer of dispersive stress between
490 flat and stepped roofs, particularly in the roughness layer. Specifically, dispersive
491 stress contributes more significantly to the total turbulent stress on flat roofs, while
492 its impact is relatively smaller on stepped roofs.

493 The efficiency of turbulence transport indicates that the values are minimized
494 at heights above the obstacle, suggesting effective momentum transfer across the
495 street canyon. For flat roofs, three peaks are evident along the street, with momen-
496 tum being transported upward in an orderly manner at the lower and upper levels,
497 and downward at the mid-level. For stepped roofs, near the ground on the left
498 street, turbulent momentum is orderly propagated downward through turbulent
499 eddies, while at the same height, the right street experiences orderly upward prop-
500 agation of turbulent momentum. Variations also exist among different stepped
501 roofs; generally, the smaller the l_{rs} and the more steps there are, the more orderly
502 the transport of turbulent momentum.

503 Lastly, it is worth noting that the current study provided a preliminary explo-
504 ration of airflow patterns in different stepped roof configurations, considering only
505 neutral stratification. Future research should delve into investigating the influence
506 of density stratification, such as thermal effects, on airflow patterns in stepped
507 roof configurations. Additionally, considering scalar transport in the stepped roof

508 configurations, for instance, pollutant dispersion, could make the research more
509 practically relevant.

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515 **Appendix A. Grid Independence Verification**

516 We conducted a grid independence verification following the approach used
517 by Huang(2022). Figure A.15 presents a comparison among the results obtained
518 using coarse (mesh size = 0.5 m ,384,000 cells), fine (mesh size = 0.333 m,
519 1,296,000 cells), and finer (mesh size = 0.25 m, 3,072,000 cells) meshes. These
520 results are based on the terrain from Simulation 4, which has the highest number
521 of steps. It is observed that the differences among these three mesh resolutions are
522 not significant, especially for the finest mesh, which shows smooth overall results
523 without any abnormal fluctuations. Additionally, a mesh density of 0.25m has
524 reached the limit for the simulation (since the roughness length is 0.1m). Com-
525 bined with the results from wind tunnel measurements discussed in Chapter 3,
526 using a 0.25m mesh resolution for this study is justified.

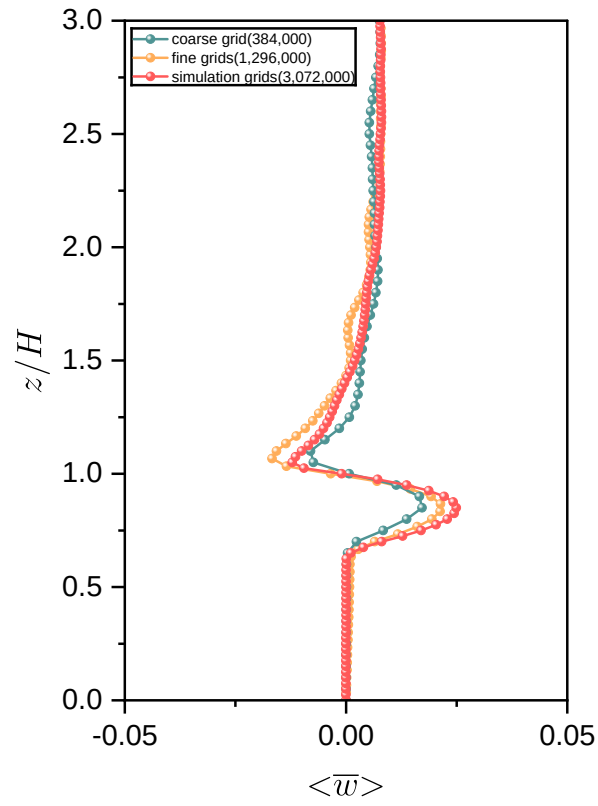


Figure A.15: Verification of grid independence. w represents the spatially and temporally averaged vertical velocity over right street.

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