

Large Eddy Simulation Study of Atmospheric Boundary Layer Flow over an Abrupt Rough-To-Smooth Surface Roughness Transition

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Research Article

Keywords:

Posted Date: November 12th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-2229327/v1>

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1 **Large Eddy Simulation Study of Atmospheric**
2 **Boundary Layer Flow over an Abrupt**
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6
7 Received: DD Month YEAR / Accepted: DD Month YEAR

8 **Abstract**

9 The atmospheric boundary layer flow downstream of an abrupt rough-to-
10 smooth surface roughness transition is studied using large eddy simulations
11 (LES) for a range of surface roughness ratios. Standard wall models assume
12 horizontal homogeneity and are inapplicable for heterogeneous surfaces. Two
13 heterogeneous-surface wall models are evaluated, one based on a local appli-
14 cation of similarity theory using a twice-filtered velocity field (BZ model) and
15 another based on a local friction-velocity obtained by blending the upstream
16 and downstream profiles (APA model). The wall shear stress and the turbu-
17 lence intensity (TI) are sensitive to the wall model while the mean streamwise
18 velocity and the total shear stress (TSS) are less sensitive. The APA model
19 is more accurate than the BZ model on comparison to previous experiments.
20 The APA model results are sensitive to the ratio of the equilibrium and the
21 internal boundary layer (IBL) heights. A value of 0.027 gives good agreement
22 with experiments over a wide range of roughness ratios. The IBL height is
23 insensitive to the turbulent quantity (TSS or TI) on which it is based. Several
24 analytical relations for the IBL height are evaluated using the LES data. Two
25 models are found to be accurate for different roughness ratios while one model
26 is reasonable over the full range investigated. A phenomenological model is

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27 developed for the TI downstream of the roughness jump using a weighted
28 average of the upstream and far-downstream profiles. The model yields rea-
29 sonable predictions for all roughness ratios investigated.

30 **Keywords** Atmospheric boundary layer · Large eddy simulation · Surface
31 heterogeneity · Internal boundary layer · Turbulence intensity

32 1 Introduction

33 The atmospheric boundary layer (ABL) is formed in the lowest part of the
34 atmosphere, up to roughly 1 to 3 km above the Earth’s surface. The Earth’s
35 surface modulates the flow in the ABL through frictional drag, evaporation
36 and transpiration, heat transfer, pollutant emission and terrain induced flow
37 modifications (Stull 1988). The flow critically affects several aspects of human
38 activity ranging from weather, air quality, agriculture to energy extraction
39 from the wind. Land surface is ubiquitously heterogeneous (Bou-Zeid et al.
40 2020) and the fluxes of momentum, heat, moisture and other passive scalars
41 imposed on the flow depend on the type of land surface. Changes in land
42 characteristics can be due to changing landscapes (e.g. a transition from a
43 water body to land) or due to changing land use (grassland, forest land and
44 cultivated or fallow land). High-fidelity large-eddy simulations (LES) of the
45 ABL flow over heterogeneously rough surfaces forms the topic of the current
46 study.

47 The momentum fluxes imposed by the ground surface on the ABL flow are
48 often characterized by an ‘aerodynamic roughness’ (denoted z_0). Such a mea-
49 sure of surface roughness encodes the form drag and skin-friction drag forces
50 imposed by ‘sub-surface’ roughness elements, or surface irregularities that are
51 much smaller than the ABL height and other length scales over the horizontal
52 directions. Other measures of surface irregularities include the mean height of
53 the irregular features and sand-grain roughness length, commonly denoted as
54 k and k_s , respectively (Abkar et al. 2004). While the three measures can be
55 used interchangeably, the latter two are more commonly used in engineering
56 literature (for $\delta/k < 40$) while the former is commonly used in geophysical
57 studies ($\delta/k > 80$), where δ is the ABL height. In this paper, we restrict at-
58 tention to the geophysical regime and to a simple configuration wherein the
59 aerodynamic roughness undergoes a step change from a relatively higher value
60 (z_{01}) to a lower value (z_{02}) in the direction that is normal to that of the mean
61 flow.

62 For an ABL flow over a homogeneously rough surface with aerodynamic
63 roughness z_{01} , without the effects of density stratification, the mean stream-
64 wise velocity obeys the logarithmic law of the wall (Stull 1988), the fluctua-
65 tions of the streamwise velocity follow a reverse logarithmic law (Stevens et al.
66 2018) and the total vertical shear stress linearly increases from its value at the
67 ground to 0 at the top of the ABL (Bou-Zeid et al. 2004). The expressions for

68 these profiles are

$$\bar{u} = (u_{*1}/\kappa) \ln(z/z_{01}), \quad (1)$$

$$\overline{u'u'} = A - B \ln(z/\delta), \quad (2)$$

$$\overline{u'w'}_{tot} = -u_{*1}^2(1 - z/\delta). \quad (3)$$

69 Here, u_{*1} is the friction velocity, $\kappa = 0.41$ is the Kármán constant, and A
 70 and B are empirical constants, z is the vertical coordinate and δ is the height
 71 of the boundary layer. The flow downstream of an abrupt surface roughness
 72 transition deviates from these ‘equilibrium’ conditions. Sufficiently far down-
 73 stream of the location of the surface roughness transition, a new equilibrium
 74 is set up wherein the flow has fully adjusted to the new surface with rough-
 75 ness z_{02} . In the intermediate region, the flow features depend on both, z_{01} and
 76 z_{02} (Garratt 1994; Chamorro and Porté-Agel 2009; Efron and Krogstad 2011;
 77 Ghaisas 2020).

78 Early studies on the flow behind an abrupt step change in surface roughness
 79 were theoretical in nature. Elliott (1958) proposed a two-layer model of the
 80 flow behind an abrupt surface roughness jump, where the lower layer is in
 81 equilibrium with the changed surface properties and the upper layer is in
 82 equilibrium with the upwind properties. The lower layer which is affected
 83 by the new surface was referred to as an ‘internal boundary layer’ (IBL).
 84 The assumption of vertically invariant shear stress within the IBL led to a
 85 discontinuity at the height where the IBL meets the undisturbed free flow.
 86 This assumption of constant shear stress within the IBL was relaxed in the
 87 theory proposed by Panofsky and Townsend (1964) where they assumed the
 88 friction velocity to be linearly varying from the ground to the IBL height.
 89 Similar two-layer models of the mean velocity were developed by Plate and
 90 Hidy (1967) and by Taylor (1969), with different assumptions for the friction
 91 velocity or eddy viscosity profiles. In contrast to the two-layer models, a few
 92 models have been developed that recognized that the flow downstream of the
 93 surface roughness jump that is affected by the changed surface roughness does
 94 not immediately attain equilibrium with the new conditions. Such three-layer
 95 models (Chamorro and Porté-Agel 2009; Abkar and Porté-Agel 2012; Ghaisas
 96 2020; Li et al. 2022) involve two layers within the IBL, termed the equilibrium
 97 boundary layer (EBL) and the transition layer.

98 Several of the above-mentioned studies require specification of the IBL
 99 height as an input. A number of analytical and/or empirical models have in
 100 turn been developed for predicting the IBL height, $\delta_i(x)$ as a function of the
 101 distance downstream of the surface roughness jump. The Elliott (1958) model
 102 is purely empirical but has been widely used as a building block in several
 103 further studies. This model as well as the models of Wood (1982) and Jegede
 104 and Foken (1999) assume that the IBL height grows as a power-law, $\delta_i \sim x^{0.8}$.
 105 The models by Panofsky and Dutton (1984) does not assume a power-law,
 106 but proposes an implicit non-linear relation for $\delta_i(x)$ that relies only on the
 107 roughness of the downstream surface, z_{02} . A similar implicit relation, but one
 108 that involves both the roughness values through its ratio $m = z_{01}/z_{02}$, was

109 proposed by Savelyev and Taylor (2005). It is unclear as to which of these
110 IBL height models is accurate, particularly over a large range of the surface
111 roughness ratio, m . One of the aims of the current study is to use high-fidelity
112 large-eddy simulation data to assess these models for the IBL height.

113 The above-mentioned theoretical studies mainly focused on modelling the
114 mean streamwise velocity behind an abrupt surface roughness transition. Second-
115 order turbulent quantities, in particular the streamwise turbulence intensity,
116 play a key role in determining fatigue loads on passive structures, such as trees
117 or buildings, and engineering systems, such as solar or wind farms, installed
118 in the ABL. Despite their importance in the design of such objects, analytical
119 models for the streamwise turbulence intensity are largely missing. In this
120 paper, we develop a simple analytical model for the streamwise turbulence
121 intensity downstream of an abrupt surface roughness jump.

122 Field observations carried out by Bradley (1968) reported velocity pro-
123 files and shear stresses downwind of both rough to smooth (RS) and smooth
124 to rough (SR) transitions, which were compared to the predictions made by
125 models of Elliott (1958) and Panofsky and Townsend (1964). Experiments on
126 RS and SR transitions in the engineering domain ($\delta/\kappa < 40$) by Antonia and
127 Luxton (1971, 1972) reported the turbulence intensity and the IBL growth in
128 addition to the velocity and shear stress profiles. Wind tunnel experiments
129 in the geophysical regime have been reported by Chamorro and Porté-Agel
130 (2009) for a RS transition with a surface roughness ratio of 83.3 and by Efros
131 and Krogstad (2011) for a SR transition. Quantities such as the mean velocity
132 profiles, the surface shear stress evolution, profiles of second-order turbulent
133 statistics and the IBL height have been reported in these studies. In particu-
134 lar, the work by Chamorro and Porté-Agel (2009) serves as a good benchmark
135 case for numerical simulations and is used as a reference case for the LES
136 presented in our work.

137 Several experiments have been reported recently (Hanson and Ganap-
138 athisubramani 2016; Li et al. 2019, 2021; Gul and Ganapathisubramani 2022)
139 that are mostly in the engineering domain. These studies have focused on the
140 one- and two-dimensional turbulent spectra and on the integral and smaller
141 length scales in the flow field behind an abrupt roughness transition. Among
142 these studies, one of the cases reported by Li et al. (2021) has a sufficiently
143 large value of δ/k for it to be of geophysical interest. The surface roughness ra-
144 tio for this case is $m \approx 21.1$, which is significantly different than the $m = 83.3$
145 (Chamorro and Porté-Agel 2009) data described above. The experimental data
146 reported in Li et al. (2021) case is also used as a benchmark for the LES pre-
147 sented in this paper.

148 Compared to theoretical studies, field observations and wind tunnel exper-
149 iments, relatively fewer number of studies have reported numerical simulations
150 of the flow over a surface roughness jump with parameters relevant to the geo-
151 physical regime. The works by Shir (1972) and Rao et al. (1974) carried out
152 two-dimensional simulations and used the Reynolds Averaged Navier-Stokes
153 (RANS) technique for turbulence closure. As all the scales of turbulence are
154 modelled instead of being resolved, RANS gives information about only the

155 averaged quantities and is heavily dependent on the model coefficients, making
156 it unreliable for problems involving a surface roughness heterogeneity (Bou-
157 Zeid et al. 2004). In contrast, three-dimensional large-eddy simulations (LES)
158 that resolve the larger scales and model only the smaller scales are better
159 suited for accurately simulating complex turbulent flows over heterogeneous
160 surfaces. A number of LES studies of the flow over heterogeneously rough
161 surfaces with different patterns of surface roughness heterogeneity have been
162 reported, ranging from an infinite number of streamwise-normal stripes (Bou-
163 Zeid et al. 2004), streamwise-aligned stripes with abrupt (Anderson et al. 2015)
164 and gradually varying roughness (Sridhar et al. 2017), oblique stripes (Anderson
165 2020), and a surface with arbitrarily distributed multi-scale, fractal-like
166 roughness elements (Anderson and Meneveau 2011). In several of these, the
167 roughness features are either fully or partially resolved using a combination of
168 an Immersed Boundary Method (IBM) and sub-surface forcing (Anderson and
169 Meneveau 2010, 2011). The requirement of resolving the near-wall geometry
170 imposes a very high computational cost and restricts several of these studies
171 to the engineering domain, i.e. to Reynolds numbers (based on the free-stream
172 velocity and the boundary layer height) of the order 10^5 to 10^7 and δ/k less
173 than roughly 40.

174 The primary challenge in LES of the flow over heterogeneous surfaces for
175 very large Reynolds numbers (order 10^{10}) and large δ/k ratios is related to
176 the modelling of the shear stresses very close to the wall. Since the nominal
177 Reynolds numbers are very high for atmospheric flows, a common practice to
178 enable simulations on reasonably-sized grids is to neglect the viscous terms
179 from the Navier-Stokes equations and to introduce an additional stress, $-u_*^2$,
180 at the bottom wall. Here, u_* is a local friction velocity that must be specified as
181 a function of the local flow conditions at every time instant in the simulation.
182 The Monin–Obukhov Similarity theory (MOST) (Monin and Obukhov 1959)
183 has provided the most commonly-used wall model formulation for LES of ABL
184 flows. For neutral conditions, MOST reduces to the law-of-the wall that de-
185 scribes momentum exchange in the surface layer. The logarithmic wind profile
186 in the surface layer predicted by this law-of-the-wall can be inverted to give the
187 friction velocity as $u_* = \langle u \rangle / (\kappa z)$, where $\langle u \rangle$ is the mean streamwise velocity
188 obtained during a simulation at a height z above the ground. This MOST-
189 based wall model is based on the assumption that the flow conditions are
190 statistically identical at all horizontal locations and has been widely adopted
191 in LES of ABL flows (Moeng 1984; Khanna and Brasseur 1997; Brasseur and
192 Wei 2010; Xie et al. 2015; Ghaisas et al. 2017). Since these assumptions of hor-
193 izontal heterogeneity do not hold for flows involving surface heterogeneities,
194 this model is inappropriate for heterogeneous cases. Two wall models account-
195 ing for heterogeneously rough ground surface that provide a way of prescribing
196 the wall shear stress in a localized manner have been proposed in the liter-
197 ature. The wall model by Bou-Zeid et al. (2004), denoted as the ‘BZ model’
198 hereafter, is based on filtering the velocity field at a scale larger than the
199 LES-filter width. The wall model by Abkar and Porté-Agel (2012), denoted
200 as the ‘APA model’, was proposed by recasting a slightly modified diagnostic

analytical model of Chamorro and Porté-Agel (2009). This wall model does not require a filtering operation but introduces a so-called blending function that allows for the mean streamwise velocity profile to vary smoothly from its upstream profile to its profile far downstream of the surface roughness jump. The APA model requires specification of the ratio of the equilibrium boundary layer to the internal boundary layer, $\alpha = \delta_e/\delta_i$, as in input parameter.

The APA model has been tested in LES (Abkar and Porté-Agel 2012) for only one value of the surface roughness ratio, $m = 83.3$, and with only one value of $\alpha = 0.027$. Furthermore, the results of Abkar and Porté-Agel (2012) focused only on the mean streamwise velocity profiles and the surface shear stress. Other quantities of interest such as the turbulence intensity, the vertical momentum flux and the internal boundary layer height evolution have not been studied using different heterogeneous-surface wall models in a systematic manner.

This paper describes results of LES of the flow over a heterogeneous surface undergoing an abrupt, rough-to-smooth surface roughness transition using a high-order numerical framework. Our aim is to assess the performance of the BZ and APA wall models by evaluating a range of turbulent statistics beyond only the mean velocity and surface shear stress. A second aim is to study the sensitivity of the APA model results to the input parameter $\alpha = \delta_e/\delta_i$, or the ratio of the equilibrium and internal boundary layer heights. We also report simulation results for different roughness ratios, $m = z_{01}/z_{02}$. Several previously developed models for the IBL height are evaluated using our LES results. Finally, a phenomenological model is proposed for the turbulence intensity profile downstream of a step change in surface roughness.

The numerical methodology and cases studied are described in Sect. 2. Details of the wall models that are assessed here are given in Sect. 2.2. Results are presented and discussed in Sect. 3 and conclusions are presented in Sect. 4.

2 Numerical Methodology

2.1 LES Methodology

LES is employed to simulate the boundary layer flow over a surface with an abrupt change in surface roughness. The incompressible, LES-filtered Navier-Stokes (NS) equations that are solved can be written as

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \quad (4)$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\tilde{u}_i \tilde{u}_j) = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (5)$$

where \tilde{u}_i is the instantaneous resolved velocity in i -direction, t is the time, and x_i with $i = 1, 2$ and 3 are the three Cartesian coordinate directions which can

236 be used interchangeably with x, y and z . The filtered pressure field is denoted
 237 by \tilde{p} and ρ is the (constant) density of air.

238 The tensor τ_{ij} is usually comprised of the viscous stresses ($-2\nu\tilde{S}_{ij}$, where
 239 ν is the viscosity and \tilde{S}_{ij} is the strain-rate tensor) and the subgrid scale (SGS)
 240 stresses ($\tau_{ij}^{sgs} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$). However, the nominal Reynolds number based
 241 on the free-stream velocity, the height of the boundary layer and the viscosity
 242 of air is of the order 10^{10} in atmospheric flows. As a result, the direct effects of
 243 viscosity are negligible over most of the domain except for a very thin region
 244 close to the bottom surface. The effects of these extremely thin viscous sub-
 245 layer and transition layer are modelled through a wall model and the viscous
 246 terms are neglected over the entire domain. The tensor τ_{ij} is thus comprised
 247 of the SGS stresses and the wall stresses, $\tau_{ij} = \tau_{ij}^{sgs} + \tau_{ij}^{wm}$.

248 The Anisotropic Minimum Dissipation (AMD) model, introduced by Rozema
 249 et al. (2015), is used to model the effect of the subgrid scales on the larger,
 250 filtered, scales of motion. The trace of the SGS stress tensor is incorporated
 251 along with the pressure while the deviatoric part is given by $\tau_{ij}^{sgs,d} = \tau_{ij}^{sgs} -$
 252 $(\tau_{kk}^{sgs}/3)\delta_{ij} = -2\nu_{sgs}\tilde{S}_{ij}$, with the eddy viscosity ν_{sgs} given by the AMD model.
 253 This model has been extensively tested previously for a variety of flow config-
 254 urations including simulations of atmospheric boundary layers and turbulent
 255 channels (Rozema et al. 2015; Abkar et al. 2016; Vreugdenhil and Taylor 2018;
 256 Zahiri and Roohi 2019; Ghaisas et al. 2020). The wall stresses, τ_{ij}^{wm} , are pre-
 257 scribed as discussed in detail in the next section.

258 The above-mentioned equations are solved using the concurrent precursor
 259 simulation method (Stevens et al. 2014). This methodology is similar to the
 260 one explained in detail in Ghaisas et al. (2020). Two computational domains
 261 of sizes ($L_x \times L_y \times L_z$) each are used. The first, ‘precursor’, domain is driven by
 262 an imposed constant pressure gradient, $f_i = -u_{*1}^2/L_z$, and has a homogeneous
 263 surface roughness, z_{01} . u_{*1} denotes the equilibrium friction velocity. A shifted
 264 periodic boundary condition (Munters et al. 2016) is applied to the precursor
 265 domain to ensure that spurious, infinitely long, streamwise-aligned streaks do
 266 not develop in the domain and contaminate the solution. The second, ‘main’,
 267 domain (see Fig. 1) has an upstream portion with aerodynamic roughness z_{01} ,
 268 followed by a transition to a surface with roughness z_{02} . The last portion of
 269 the main domain is a ‘fringe’ region, wherein the flow is nudged towards the
 270 same upstream conditions as in the precursor domain using the additional
 271 forcing term f_i . The surface roughness in the fringe region is the same as in
 272 the upstream and precursor domains, i.e. z_{01} . The top boundary ($z = L_z$) is
 273 imposed with no-penetration, free-slip conditions and all the horizontal (x, y)
 274 boundaries are periodic. The bottom boundary is a no-penetration wall, and
 275 a shear stress is applied using a wall model.

276 The ‘PadeOps-igrid’ code (Subramaniam et al. 2021) developed over the
 277 years is used for the simulations. This code uses Fourier-spectral discretization
 278 in the horizontal (x, y) directions, 6th-order staggered compact finite-difference
 279 scheme in the vertical (z) direction and a 3rd-order Runge-Kutta method for
 280 time advancement. The code is well validated and has been used previously

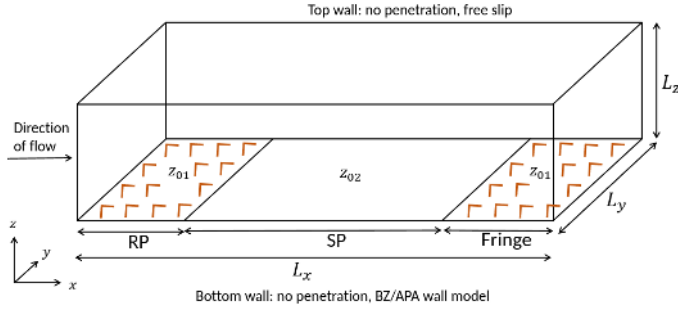


Fig. 1 Schematic of the ‘main’ domain showing different dimensions of the computational domain. Boundary conditions for the top and bottom wall are shown. z_{01} and z_{02} are the aerodynamic roughness for the rough surface and the smooth surface respectively. The fringe region has the same roughness as the upwind of the step jump; RP stands for rough patch, SP stands for smooth patch

281 for several problems including rough-wall turbulent channels (Ghate and Lele
 282 2020), stratified and unstratified atmospheric boundary layers (Ghate and Lele
 283 2017), and problems involving wind turbines or farms (Ghate et al. 2020;
 284 Ghaisas et al. 2020; Howland et al. 2020).

285 2.2 Wall Models

286 The effect of viscosity is modelled by introducing the term τ_{ij}^{wm} in the total
 287 stress in the Navier-Stokes equations. Since viscous effects are important only
 288 close to the wall, τ_{ij}^{wm} is zero at all points in the domain except at the bottom
 289 wall, $z = 0$. Furthermore, only the vertical shear components (i.e. τ_{i3}^{wm} with
 290 $i = 1, 2$) are non-zero.

291 The standard ‘equilibrium’ wall model based on the Monin-Obukhov Sim-
 292 ilarity Theory (Moeng 1984) first estimates the magnitude of the mean shear
 293 stress ($-\langle u_* \rangle^2$) by inverting the logarithmic law-of-the-wall. The horizontally-
 294 averaged streamwise velocity ($\langle \tilde{u}_1 \rangle$) available during the LES at the first grid
 295 point from the wall (i.e. $z = \Delta z/2$) is used in these models to determine the
 296 mean shear stress. The mean shear stress is then distributed into its two compo-
 297 nents, i.e. τ_{13}^{wm} and τ_{23}^{wm} , with each component being proportional to the
 298 corresponding component of the instantaneous local filtered horizontal veloci-
 299 tity,

$$\tau_{i3}^{wm}(x, y, 0) = -\langle u_* \rangle^2 \frac{\tilde{u}_i}{(\tilde{u}_1^2 + \tilde{u}_2^2)^{1/2}}, \quad \langle u_* \rangle = \frac{\langle u_1(\Delta z/2) \rangle \kappa}{\ln(\Delta z/2z_0)}. \quad (6)$$

300 Here, $\langle \dots \rangle$ denotes a horizontal averaging operation. This model is inapplicable
 301 for flows over heterogeneously rough surfaces since it is inappropriate to carry
 302 out a horizontal average in such flows. A few studies tried to overcome this
 303 problem by applying the logarithmic law-of-the-wall in a strictly local sense

304 (Albertson and Parlange 1999). However, it is easily shown, using the Cauchy-
 305 Schwartz inequality, that this leads to an over-prescription of the wall shear
 306 stress.

307 Two previously-proposed wall models that try to account for non-equilibrium
 308 effects induced by the presence of the surface roughness step are evaluated in
 309 this paper. These models are described next.

310 The first model evaluated here was proposed by Bou-Zeid et al. (2004)
 311 and is denoted as the ‘BZ’ wall model in this paper. This strictly local wall
 312 model uses a velocity field that is filtered using a width of size 2Δ , where
 313 $\Delta = (\Delta x \Delta y \Delta z)^{1/3}$ is the characteristic grid size. Referring to this velocity
 314 field filtered at the 2Δ -scale as \widehat{u}_i , the wall shear stress is given by

$$\tau_{i3}^{um}(x, y, 0) = -[u_*(x, y)]^2 \frac{\widehat{u}_i(x, y, \Delta z/2)}{\sqrt{\widehat{u}_1(x, y, \Delta z/2)^2 + \widehat{u}_2(x, y, \Delta z/2)^2}}, \quad (7)$$

315 where the local friction velocity is given by assuming that the 2Δ -filtered
 316 horizontal velocity satisfies the law-of-the-wall locally,

$$u_*(x, y) = \frac{\kappa}{\ln[\Delta z/2z_0(x, y)]} \sqrt{\widehat{u}_1(x, y, \Delta z/2)^2 + \widehat{u}_2(x, y, \Delta z/2)^2}. \quad (8)$$

317 In this study, $z_0(x, y)$ is either z_{01} or z_{02} depending on the roughness of the
 318 underlying surface at the horizontal location given by coordinates (x, y) . This
 319 model reduces the over-prescription of the mean wall shear stress since the
 320 2Δ -filtered velocity field has much smaller fluctuations. This model also does
 321 not require a horizontal averaging operation and hence can be applied to het-
 322 erogeneously rough surfaces.

323 The second wall model evaluated here is that originally proposed by Chamorro
 324 and Porté-Agel (2009) and modified by Abkar and Porté-Agel (2012). We de-
 325 note this as the ‘APA’ model. This model uses the same formulation as Eq. 7
 326 but it does not rely on the assumption that the local friction velocity satis-
 327 fies a local logarithmic law-of-the-wall immediately downstream of an abrupt
 328 surface roughness transition. Instead, this model explicitly accounts for the
 329 fact that the local friction velocity changes along the streamwise direction
 330 and gradually approaches its equilibrium value by using a blending function
 331 $\lambda(x, z)$. The local friction velocity is given by

$$u_{*2}(x) = \frac{\kappa}{\ln(\Delta z/2z_{02})} \frac{\overline{[\widehat{u}_1(x, \Delta z/2) - \lambda(x, \Delta z/2) \frac{u_{*1}}{\kappa} \ln(\Delta z/2z_{01})]}}{[1 - \lambda(x)]}, \quad (9)$$

332 Here, $\overline{(\cdot)}$ denotes averaging in the spanwise (y) direction. u_{*1} is the fric-
 333 tion velocity in the upstream region, which is also the friction velocity in
 334 the precursor domain since the flow in the upstream region is driven by the
 335 flow in the precursor domain. The blending function is modelled as $\lambda(x, z) =$
 336 $\ln[z/\delta_e(x)]/\ln[\delta_i(x)/\delta_e(x)]$, and is evaluated at $x = \Delta z/2$ in Eq. 9. Here, $\delta_i(x)$

337 is the height of the internal boundary layer (IBL) at a distance x from the loca-
 338 tion of the abrupt transition in surface roughness. The IBL height is specified
 339 using the empirical relation proposed by Elliott (1958),

$$\delta_i(x) = z_{02} \left[0.75 - 0.03 \ln \left(\frac{z_{02}}{z_{01}} \right) \right] \left(\frac{x}{z_{02}} \right)^{0.8}. \quad (10)$$

340 In this equation, $\delta_e(x)$ is the equilibrium boundary layer height and was as-
 341 sumed by Abkar and Porté-Agel (2012) to be a constant fraction of the IBL
 342 height, $\delta_e(x) = \alpha \delta_i(x)$. This model is applicable only in the region where the
 343 surface roughness has abruptly changed from its upstream value to z_{02} because
 344 $\lambda < 1$ in this region. The value of λ is set to zero once the equilibrium bound-
 345 ary layer crosses the first computational grid point, i.e. once $\delta_e(x) > \Delta z/2$.
 346 Beyond this streamwise location, the model reduces to the BZ model with the
 347 surface roughness equal to z_{02} .

348 In the entirety of the precursor domain, in the portion of the main domain
 349 that is upstream of the abrupt surface roughness transition, and in the fringe
 350 portion of the main domain where the flow is nudged towards the same flow
 351 field as in the precursor domain, the surface roughness is uniformly z_{01} . In
 352 these three regions, the BZ wall model with surface roughness equal to z_{01} is
 353 applied. In the portion of the main domain between the abrupt transition and
 354 the fringe, either the BZ model (Eqs. 7 and 8) with roughness z_{02} or the APA
 355 model (Eqs. 7 and 9) is applied. We refer to these two combinations as ‘BZ’
 356 model and ‘APA’ model respectively.

357 2.3 Cases Simulated

358 The computation domain dimensions are selected as per the experiments re-
 359 ported by Chamorro and Porté-Agel (2009), $(L_x, L_y, L_z) = (3.84, 0.64, 0.4)$ m.
 360 The origin of the coordinate system is placed at the location of the roughness
 361 jump which is situated at 0.96 m from the left end of the domain. The upstream
 362 surface aerodynamic roughness height is $z_{01} = 0.5$ mm, as used by Chamorro
 363 and Porté-Agel (2009). The downstream surface has different roughness val-
 364 ues as described below. All spatial dimensions are normalized by 0.4/3 m so
 365 that the vertical height of the domain, which is 0.4 m in the experiments of
 366 Chamorro and Porté-Agel (2009), becomes 3 non-dimensional units. Figure 2
 367 shows the different portions of the computational domain in scaled units.

368 A total of nineteen LES simulations are carried out. The cases are selected
 369 so as to cover different roughness ratios ($m = z_{01}/z_{02}$), wall models, different
 370 grid sizes and different values of the parameter $\alpha = \delta_e/\delta_i$ which is an input to
 371 the APA model.

372 First, a set of six simulations for $m = 83.3$ covers the two wall models (BZ
 373 and APA) discussed in the preceding section and three grid sizes comprised
 374 of $128 \times 32 \times 32$ (G1), $192 \times 64 \times 64$ (G2) and $240 \times 80 \times 80$ (G3) points. It
 375 should be noted that this number of points is used to discretize each of the two

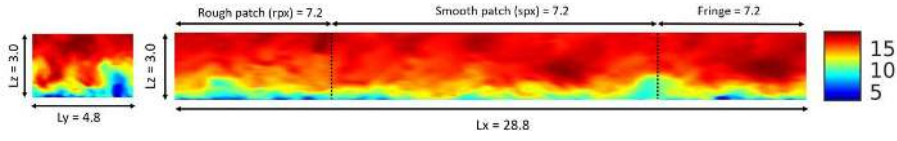


Fig. 2 Contours of the streamwise velocity at an arbitrary time instant from a $240 \times 80 \times 80$ simulation for $m = 83.3$ using the BZ wall model. Dimensions of the main computational domain in the (a) $y-z$ plane and (b) $x-z$ plane are shown. Upstream rough patch, surface roughness step, downstream smooth patch and the fringe region are also marked

Table 1 Summary of cases simulated. Cases 1 to 16 have a surface roughness transition from $z_{01} = 0.5$ mm to z_{02} at $x = 0$ in the main domain and surface roughness is z_{01} everywhere in the precursor domain. Cases number 17 to 19 are homogeneously rough with the mentioned z_0 in both domains. Number of grid points mentioned are per domain. Actual number of points used in each simulation is twice that mentioned below.

Case No.	Grid	Wall Model	$m = z_{01}/z_{02}$	$\alpha = \delta_e/\delta_i$	z_{02} (mm)
1	$240 \times 80 \times 80$	BZ	83.3	-	0.006
2	$240 \times 80 \times 80$	APA	83.3	0.027	0.006
3	$192 \times 64 \times 64$	BZ	83.3	-	0.006
4	$192 \times 64 \times 64$	APA	83.3	0.027	0.006
5	$128 \times 32 \times 32$	BZ	83.3	-	0.006
6	$128 \times 32 \times 32$	APA	83.3	0.027	0.006
7	$240 \times 80 \times 80$	BZ	20	-	0.025
8	$240 \times 80 \times 80$	APA	20	0.027	0.025
9	$240 \times 80 \times 80$	BZ	125	-	0.004
10	$240 \times 80 \times 80$	APA	125	0.027	0.004
11	$240 \times 80 \times 80$	APA	20	0.054	0.025
12	$240 \times 80 \times 80$	APA	20	0.108	0.025
13	$240 \times 80 \times 80$	APA	83.3	0.054	0.006
14	$240 \times 80 \times 80$	APA	83.3	0.108	0.006
15	$240 \times 80 \times 80$	APA	125	0.054	0.004
16	$240 \times 80 \times 80$	APA	125	0.108	0.004
17	$240 \times 80 \times 80$	BZ	1	-	$z_0 = 0.025$ mm everywhere
18	$240 \times 80 \times 80$	BZ	1	-	$z_0 = 0.006$ mm everywhere
19	$240 \times 80 \times 80$	BZ	1	-	$z_0 = 0.004$ mm everywhere

376 domains per simulation, so that the actual number of computational points in
 377 each simulation is twice that mentioned above and in Table 1.

378 The second set of simulations covers two additional values of $m = 20$ and
 379 125 and the two wall models. Following a grid sensitivity study, we use the
 380 finest grid (G3) for the four runs in this set.

381 In all the cases mentioned above that involve the APA wall model, the
 382 value of $\alpha = 0.027$ is used, where $\alpha = \delta_e/\delta_i$, is the ratio of the equilibrium
 383 to the internal boundary layer height. To study the sensitivity to this input
 384 parameter, six additional cases using the APA model, with $\alpha = 0.054$ and
 385 0.108, for the three surface roughness ratios ($m = 20, 83.3, 125$) on the G3
 386 grid are carried out.

387 Finally, simulations over homogeneously rough surfaces with the tabulated
 388 roughness values are conducted. These cases are useful for developing an an-
 389alytical model for the turbulence intensity described later in this paper.

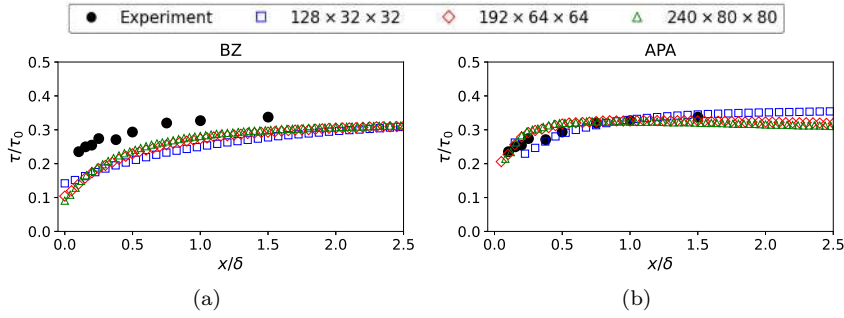


Fig. 3 Streamwise evolution of wall shear stress after the abrupt surface roughness transition for different grid sizes using (a) BZ and (b) APA wall models. Experimental results are from Chamorro and Porté-Agel (2009)

390 The upstream friction velocity is $u_{*1} = 0.5473$ m/s following Chamorro and
 391 Porté-Agel (2009). All the simulations are carried over 100 non-dimensional
 392 time units (normalized using $\delta_{exp} = 0.4$ m and u_{*1} as reference scales). Statist-
 393 cal averaging is performed over the last 60 time units. Averaging is performed
 394 in time and along the horizontal (x, y) directions for the precursor domain and
 395 over time and the spanwise (y) direction in the main domain.

396 3 Results & Discussion

397 3.1 Grid Convergence

398 Sensitivity of different statistics of the ABL flow to the grid resolution used
 399 in the LES are studied first. Besides using two wall models and three different
 400 grids, the results are also compared with experimental data of Chamorro and
 401 Porté-Agel (2009) wherever available.

402 Figure 3 shows the surface shear stress after the change in surface roughness
 403 for different grid sizes using the BZ and APA wall models for $m = 83.3$. Here,
 404 the shear stress at the bottom wall downstream of the surface roughness jump
 405 (τ) is normalized by the surface shear stress upstream of the jump (τ_0). The
 406 LES data show appreciable change in magnitude when compared between the
 407 $128 \times 32 \times 32$ and $192 \times 64 \times 64$ grid cases. An additional simulation for grid
 408 size of $240 \times 80 \times 80$ is also compared and it is observed that there is little
 409 change in magnitudes when compared with the $192 \times 64 \times 64$ grid.

410 The temporally and spanwise averaged streamwise velocities at two down-
 411 stream locations ($x/\delta = 0.5, 1.0$) after the roughness jump are presented in
 412 Fig. 4. These profiles are almost insensitive to the grid resolution for both
 413 models. Small differences are seen close to the top of the domain, where the
 414 velocity profiles are seen to agree better with the upstream logarithmic ‘law of
 415 the wall’ profile, Eq. 1, with increasing grid resolution. Closer to the bottom
 416 boundary, the velocity accelerates due to the reduced surface roughness. This
 417 acceleration is the same for all grids for the BZ as well as APA wall models.

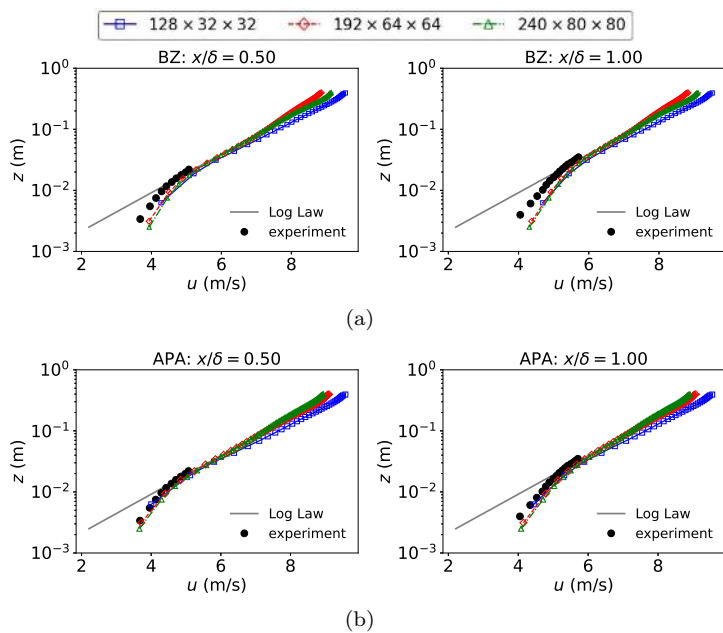


Fig. 4 Vertical profiles of the mean streamwise velocity at different downstream locations after the abrupt surface roughness transition for different grid sizes for $m = 83.3$ using (a) BZ and (b) APA wall models

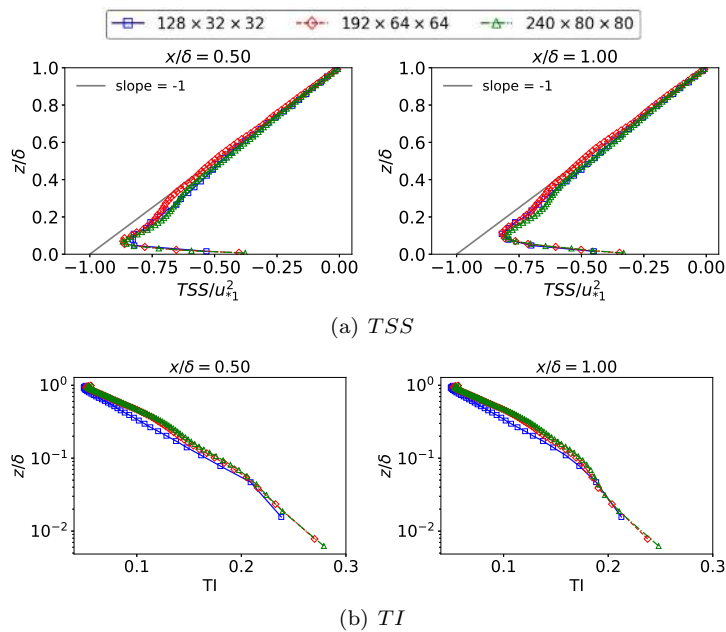


Fig. 5 Vertical profiles of (a) TSS and (b) TI at different downstream locations after the roughness jump using different grid sizes and the APA wall model for $m = 83.3$

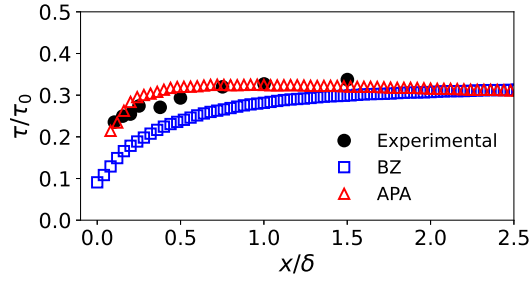


Fig. 6 Streamwise evolution of wall shear stress for $m = 83.3$ on grid G3 using BZ and APA wall models compared to the experimental data of Chamorro and Porté-Agel (2009)

418 The streamwise turbulence intensity (TI) and the total shear stress (TSS)
 419 are shown at the same downstream locations as the streamwise velocity for
 420 the APA wall model in Fig. 5. The TSS has contributions due to the resolved
 421 scales, subgrid scales and the wall model i.e. $TSS = \overline{u'w'} + \overline{\tau_{13}^{sgs}} + \overline{\tau_{13}^{wm}}$. The
 422 TSS profiles are almost independent of the number of grid points employed.
 423 The turbulence intensity is defined as the ratio of the standard deviation of
 424 the streamwise velocity to the mean velocity,

$$TI = \sqrt{\overline{u'^2}}/\bar{u}. \quad (11)$$

425 The TI increases when going from the coarsest to the intermediate grid, but
 426 is unchanged over the two finest grids employed here. This indicates that
 427 a computational grid with $240 \times 80 \times 80$ points is sufficient to obtain grid-
 428 independent results. All subsequent simulations utilize these many grid points.

429 3.2 Sensitivity of ABL Statistics to Wall Models

430 Sensitivity of the results to the wall model employed is studied next.

431 Following the surface roughness jump at $x = 0$, the shear stress applied by
 432 the new smooth surface on the flow is smaller compared to that applied by the
 433 upstream rough surface. The wall shear stresses obtained from the LES runs
 434 of different wall models are compared to the experimental data of Chamorro
 435 and Porté-Agel (2009) in Fig. 6. It is seen that the BZ model under-predicts
 436 the wall shear stress values while the APA wall model results agree well with
 437 the experimental results. Furthermore, Fig. 3 shows that, on refining the grid,
 438 the values converge towards the experimental results for both models. The
 439 convergence is monotonic in case of BZ, but quite slow. This indicates that
 440 the BZ model would yield good agreement with the experiments on a very
 441 refined mesh.

442 The LES results using the APA model are in much better agreement with
 443 the experimental results than those using the BZ model. This is true for all
 444 grid sizes studied, but the convergence is not monotonic (see Fig. 3). A careful
 445 inspection of Fig. 6 shows that the computed shear stress values using the

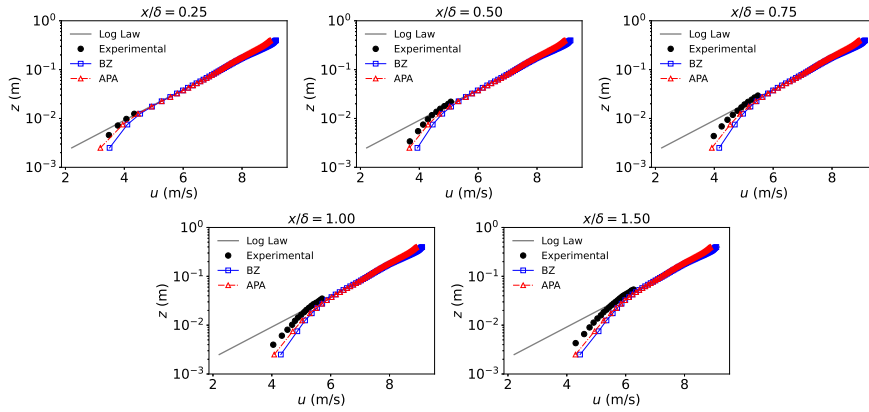


Fig. 7 Vertical profiles of mean streamwise velocity at different locations downstream of the abrupt surface roughness transition on grid G3 for $m = 83.3$ using different wall models

446 APA model reduce slightly between $x/\delta = 0.5$ and $x/\delta = 1.5$. As discussed
 447 later, in Sect. 3.3, this feature is absent for larger values of the ratio $\alpha = \delta_e/\delta_i$.

448 Figure 7 compares the upstream logarithmic law-of-the-wall profile, the
 449 experimental results (Chamorro and Porté-Agel 2009) and the mean velocity
 450 profiles obtained from the LES on the finest grids using the two wall models
 451 at several locations downstream of the roughness jump for $m = 83.3$. It is
 452 clear that the LES results adhere to the law-of-the-wall closely above a certain
 453 height. This height above which the downstream and upstream profiles are
 454 identical is called the internal boundary layer (IBL) height and is discussed in
 455 detail later. Below the IBL height, the APA model results are in slightly better
 456 agreement with the experimental results than the BZ model results. This is
 457 consistent with the under-predictions of the surface shear stresses found in
 458 Fig. 6.

459 Vertical profiles of TSS obtained from different regions of the simulation
 460 domains are shown in Fig. 8. For a fully-developed statistically stationary
 461 turbulent boundary layer in a half-channel, the TSS normalized by its value at
 462 the bottom wall (u_{*1}^2) is expected to follow a slope of -1 reducing in magnitude
 463 from 1 at the wall to 0 at the top (Eq. 3). The profile obtained from averaging
 464 over the precursor domain (surface roughness z_{01} everywhere) agrees very well
 465 with this theoretically expected line. The profile obtained by averaging over
 466 the upstream portion of the main simulation domain (before $x = 0$ with surface
 467 roughness z_{01}) also agrees well with this theoretically expected line.

468 The profiles of TSS averaged over the spanwise coordinate at different
 469 locations downstream of the surface roughness jump ($x > 0$) are found to
 470 be insensitive to the wall model. Close to the bottom wall, the magnitude of
 471 the TSS is smaller compared to its upstream value, consistent with the axial
 472 evolution of the surface shear stress shown in Fig. 6 and with the fact that
 473 the surface roughness reduces at $x = 0$, i.e. $z_{02} < z_{01}$. Furthermore, it is seen
 474 that the TSS varies linearly from its value at the wall to the top of the IBL

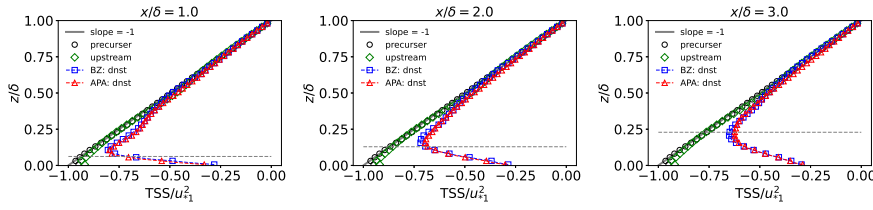


Fig. 8 Vertical profiles of TSS at different locations downstream of the abrupt surface roughness transition on grid G3 for $m = 83.3$ using different wall models. The grey dashed line represents the IBL height at each x/δ location and ‘dnst’ stands for downstream.

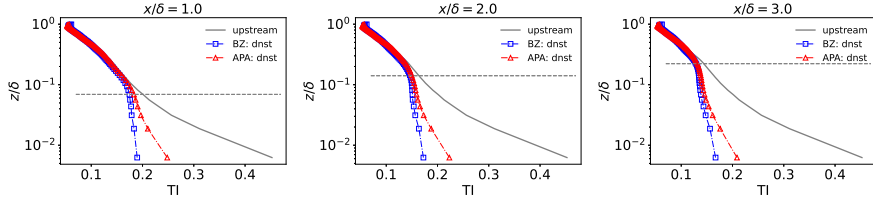


Fig. 9 Vertical profiles of TI at different locations downstream of the abrupt surface roughness transition on grid G3 for $m = 83.3$ using different wall models. The grey dashed line represents the IBL height at each x/δ location and ‘dnst’ stands for downstream.

475 (marked by dashed gray lines). This indicates that several early analytical
 476 models (Panofsky and Townsend 1964; Chamorro and Porté-Agel 2009) were
 477 based on an incorrect assumption of constant shear stress within the IBL, but
 478 supports the assumption made in a recent analytical model by Ghaisas (2020).

479 Unlike the TSS , the TI downstream of the step is very much sensitive to
 480 the wall models as shown in Fig. 9. The profile upstream of the roughness jump
 481 has larger values of TI close to the wall, once again consistent with the fact
 482 that the configuration being studied is a rough-to-smooth surface transition,
 483 or $z_{02} < z_{01}$. The TI value at the wall obtained using the APA model is
 484 larger than that obtained using the BZ model, consistent with the surface
 485 shear stresses obtained using these two wall models (see Fig. 6). In each panel
 486 of Fig. 9, the influence of the changed roughness on the downstream profiles
 487 is seen to be prominent near the wall but it disappears after a certain height
 488 similar to the mean velocity profiles. This again indicates the presence of an
 489 IBL within which the effects of the changed surface roughness are confined.

490 To study the evolution of the internal boundary layer, the IBL heights extracted
 491 from the LES data based on two turbulent statistics, TSS and TI , are
 492 presented in Fig. 10. The dashed vertical line marks the jump in aerodynamic
 493 roughness from rough to smooth. For each profile, the IBL height is deter-
 494 mined as the smallest distance from the bottom wall where the upstream and
 495 downstream profiles differ by less than 10%. The IBL profiles for both TSS
 496 and TI are insensitive to the wall models as seen from Figs. 10a and 10b. Also,
 497 it is evident from Fig. 10c that the IBL based on TSS profiles are similar to

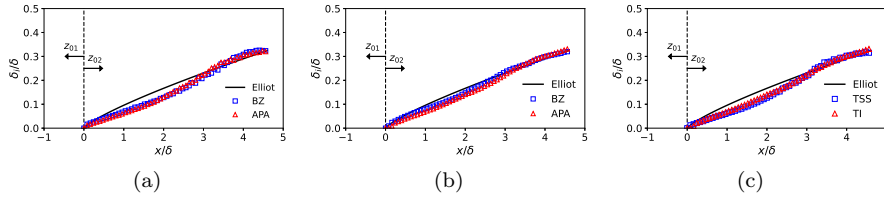


Fig. 10 Streamwise evolution of the height of the internal boundary layer for $m = 83.3$ based on (a) *TSS* and (b) *TI* using the two wall models. (c) Comparison of IBL heights based on the two turbulent statistics using the APA wall model. Symbols denote LES data using grid G3. Lines denote predictions of the empirical model of Elliott (1958)

498 those based on *TI* profiles. Finally, the empirical relation proposed by Elliott
 499 (1958), Eq. 10, for the IBL height is seen to be quite accurate for $m = 83.3$.

500 3.3 Sensitivity of APA wall model to the ratio of internal and equilibrium 501 boundary layer heights

502 As discussed in Sect. 2.2, the ratio of the equilibrium boundary layer height
 503 (δ_e) to the internal boundary layer height (δ_i), i.e. $\alpha = \delta_e/\delta_i$, is an input
 504 parameter to the APA model. We study the sensitivity of the APA model LES
 505 results to this parameter by considering three different values of $\alpha = 0.027$,
 506 0.054 and 0.108 . This sensitivity is studied for three values of surface roughness
 507 ratios, $m = z_{01}/z_{02} = 25$, 83.3 and 125 . The upstream roughness z_{01} is kept
 508 unchanged and the downstream roughness is altered in three cases to get
 509 $m = 20$, 83.3 and 125 . A total of nine LES are analyzed in this subsection.

510 Fig. 11a shows the streamwise evolution of the wall shear stress for the
 511 different cases. For $m = 83.3$ the results are compared with the experimental
 512 data (Chamorro and Porté-Agel 2009). The $m = 20$ LES results are compared
 513 to the experimental data at a slightly different value of $m \approx 21.1$ reported
 514 by Li et al. (2021). Due to lack of experimental data for the last case, RANS
 515 simulations by Shir (1972) are used for comparison.

516 The wall shear stresses obtained from the LES using the APA wall model
 517 are clearly sensitive to the parameter α . This is contrary to what was sug-
 518 gested, but not explicitly shown, in the study of Abkar and Porté-Agel (2012).
 519 For $m = 20$ as well as $m = 83.3$, the agreement with the experimental results
 520 is the best for $\alpha = 0.027$. This is seen more quantitatively in Table 2, where
 521 the L_2 norms of the relative errors, expressed as a percentage, are shown. The
 522 tabulated values are calculated as

$$\epsilon = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{\tau - \tau_{\text{exp}}}{\tau_0} \right)^2} \times 100, \quad (12)$$

523 where N is the number of measurement points. The error norms are smallest
 524 for $\alpha = 0.027$ for both $m = 20$ and 83.3 . The value $\alpha = 0.027$ was recom-
 525 mended by Abkar and Porté-Agel (2012) and is found to be appropriate

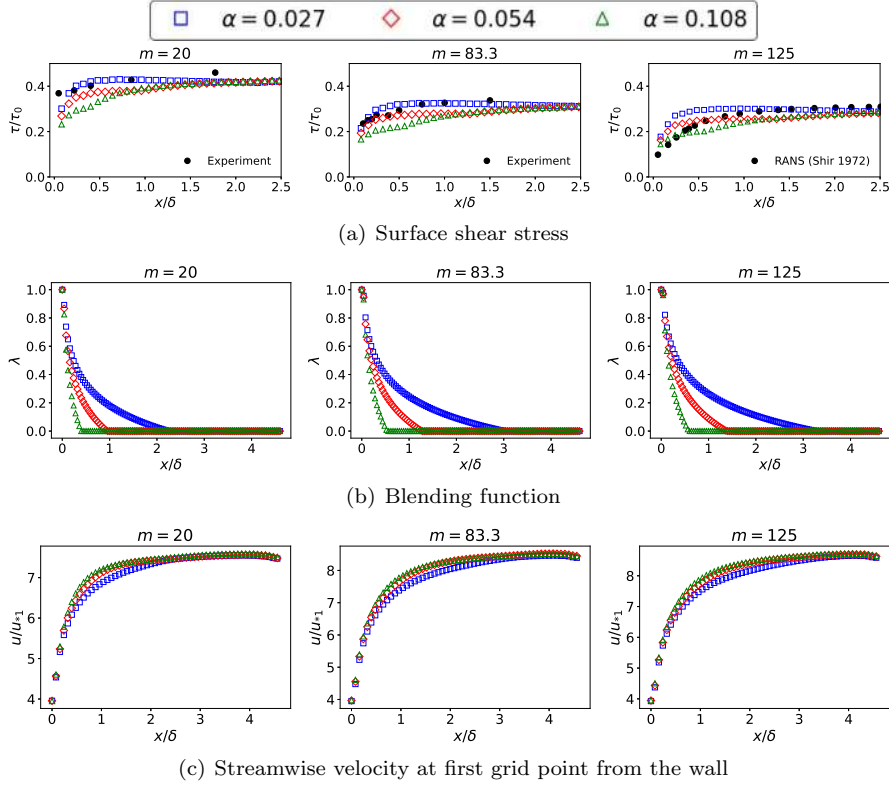


Fig. 11 Streamwise evolution of (a) wall shear stress (b) λ and (c) mean streamwise velocity at $z = \Delta z/2$ computed for different roughness ratios m using the APA model with different values of α on grid G3. In panel (a) the experimental data are from Li et al. (2021) for $m = 20$ and from Chamorro and Porté-Agel (2009) for $m = 83.3$. The RANS data for $m = 125$ are from Shir (1972)

Table 2 Error norms between the surface shear stress values obtained from LES and from previous experiments, calculated using Eq. 12, for different α and m values.

$m = z_{01}/z_{02}$	$\alpha = 0.027$	$\alpha = 0.058$	$\alpha = 0.108$
20	2.14%	4.35%	7.9%
83.3	2.12%	3.21%	6.21%

526 over a range of m values with the current numerical framework involving a
 527 high-order compact finite-difference scheme in the vertical direction.

528 The LES results for $m = 125$ are in fair agreement with the RANS results.
 529 However, due to the strong assumptions involved in RANS models, these can-
 530 not be used as a benchmark to assess LES simulation results. However, the
 531 value of $\alpha = 0.027$ is likely to be appropriate for values of m beyond 83.3
 532 as well, although this needs to be confirmed by future experiments or wall-
 533 resolved DNS or LES simulations.

534 Fig. 11a also shows that the surface shear stress values attained far down-
 535 stream of the transition are independent of the value used for α . To understand
 536 the behaviour of the APA wall model in the intermediate region further, pro-
 537 files of the blending function, $\lambda(x, \Delta z/2)$, and the spanwise-averaged velocity
 538 at the first off-wall grid point, $\bar{u}_1(x, \Delta z/2)$, are shown in Figs. 11b and 11c.
 539 An increase in α leads to a significant decrease in λ for a given x , consistent
 540 with the model used for λ . In other words, increasing the α leads to the λ
 541 profile approaching its far-downstream value of 0 faster. In conjunction with
 542 Eq. 9, this would at first suggest that the surface shear stress approaches its
 543 far-downstream value at a smaller x location for a larger value of α . Figure 11
 544 however shows the opposite is true, namely the surface shear stress approaches
 545 its far-downstream value faster for smaller α . This is explained by the small
 546 differences in the evolution of the streamwise velocity at the first off-wall grid
 547 point (Fig. 11b) due to different α values.

548 Other statistics such as streamwise velocity, TSS and TI are plotted for
 549 different m and α values in Fig. 12. Except for small differences for different
 550 values of α for $m = 20$, these quantities are mostly insensitive to α .

551 3.4 Sensitivity to roughness ratio

552 Sensitivity to the roughness ratio is studied by analysing simulation results
 553 for $m = 20, 83.3$ and 125 . The APA wall model with $\alpha = 0.027$ is used for all
 554 the runs.

555 Figure 13a shows that for a configuration with smaller roughness ratio,
 556 the shear stress downstream of the surface roughness jump is larger. This is
 557 consistent with intuition since a smaller $m = z_{01}/z_{02}$ for the same z_{01} implies a
 558 downstream surface that exerts more resistance to the flow. The change in the
 559 downstream surface shear stress between $m = 83.3$ and 125 is smaller than
 560 that between $m = 20$ and 83.3 . This suggests that the downstream surface
 561 shear stresses will asymptotically approach limiting values for higher values of
 562 m .

563 Due to smaller wall shear stress for higher m values, the flow accelerates
 564 faster after the roughness jump as seen in Fig. 14a. It is observed that for
 565 the largest two values of m studied here, the change in \bar{u} is insignificant. The
 566 same trends are seen to hold for the TSS and TI profiles (Figures 14b and
 567 14c, respectively). A lower value of m indicates a rougher surface after the
 568 step jump, which increases the turbulent statistics in the flow. As a result,
 569 TSS and TI have larger magnitudes within the IBL for smaller values of m .
 570 Similar to \bar{u} , the changes in TSS and TI are insignificant between $m = 83.3$
 571 and 125 . Finally, Fig. 13b shows that the IBL height evolution is very similar
 572 for all three surface roughness ratios.

573 Several analytical models (Panofsky and Townsend 1964; Chamorro and
 574 Porté-Agel 2009; Ghaisas 2020) for the mean velocity downstream of a surface
 575 roughness jump as well as the APA wall model require the internal boundary
 576 layer height as an input. A number of empirical and/or physics-based models

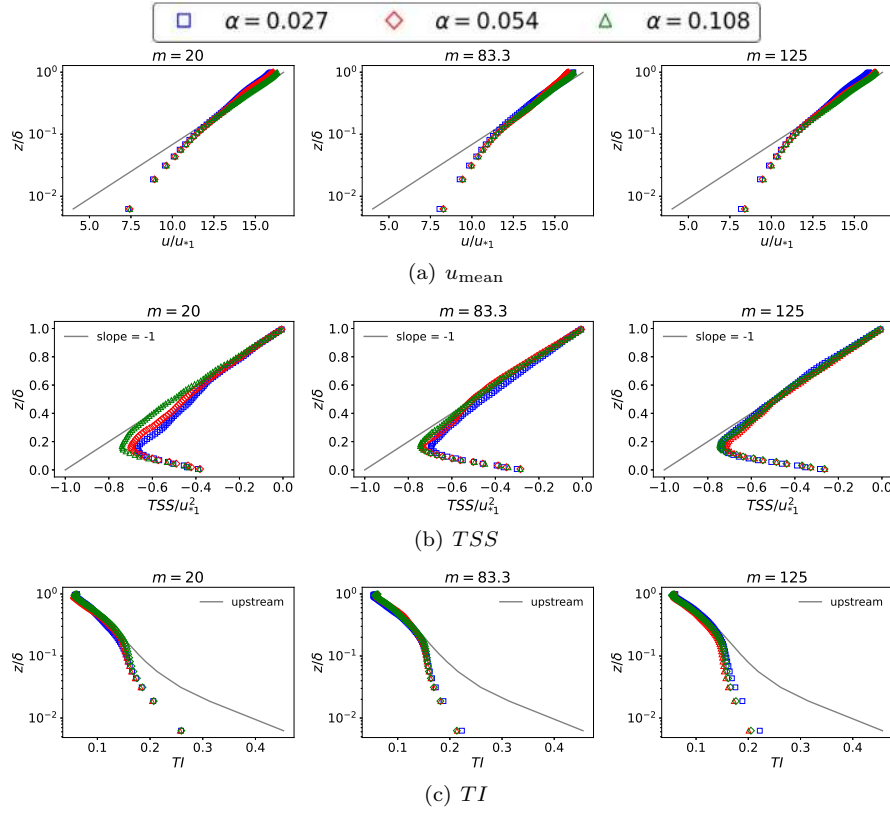


Fig. 12 Vertical profiles of (a) mean streamwise velocity, (b) TSS and (c) TI for different roughness ratios m using different α in the APA model at the downstream location of $x/\delta = 2.0$ on grid G3

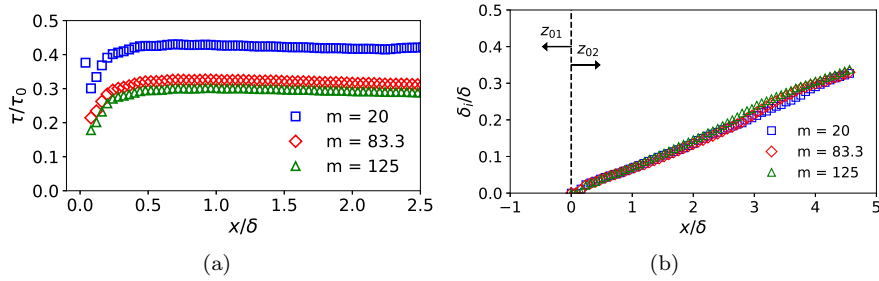


Fig. 13 Streamwise evolution of (a) wall shear stress and (b) IBL height based on the turbulence intensity from LES using the APA wall model for different roughness ratios on grid G3

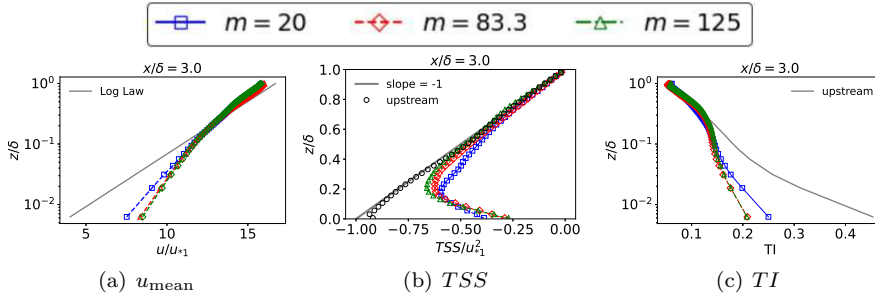


Fig. 14 Vertical profiles of (a) mean streamwise velocity, (b) TSS and (c) TI at a downstream location of $x/\delta = 3.0$ for different m values using the APA wall model on grid G3

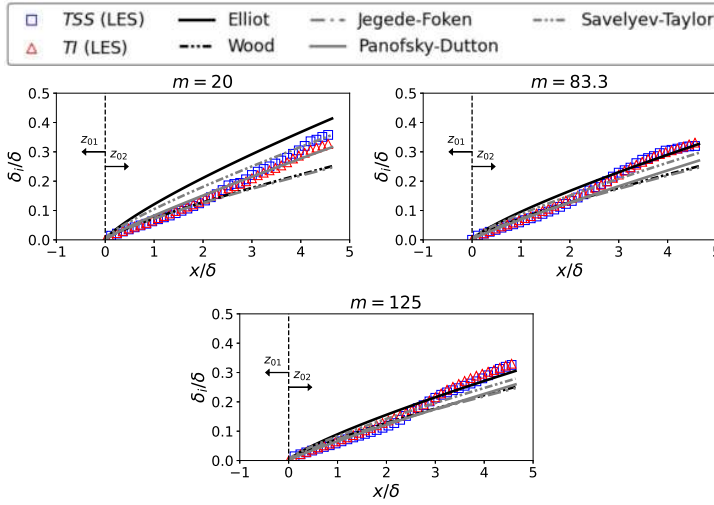


Fig. 15 Comparison of IBL heights obtained from LES (based on TSS and TI) to predictions of five IBL models listed in Table 3 for different m values using the APA model on grid G3

577 have in turn been developed for the IBL height. Fig. 15 compares the IBL
 578 height obtained from the LES using the APA wall model with predictions of
 579 five different IBL models. A quantitative assessment of the errors between the
 580 LES results and the IBL model predictions is shown in Table 4. Details of the
 581 models evaluated here are given in Table 3. Some of these models require the
 582 solution of a nonlinear equation which is achieved using the ‘fsolve’ function
 583 in Matlab. The prediction of the Elliott (1958) model serves as a good starting
 584 guess for the root-finding procedure at each x .

585 The models by Wood (1982) and by Jegede and Foken (1999) agree with
 586 the LES results till about $x/\delta \approx 2.5$ but under-predict the LES results beyond
 587 this. These two models show significant errors, between 11% and 15% for the
 588 three surface roughness ratios and depending upon whether the TI or the
 589 TSS profiles are used to calculate the IBL heights from the LES results. The

Table 3 List of IBL models evaluated using the LES data

Author(s)	IBL Model
Elliott (1958)	$\delta_i = z_{02} [0.75 - 0.03 \ln(1/m)] (x/z_{02})^{0.8}$
Wood (1982)	$\delta_i = 0.28 [\max(z_{01}, z_{02})] [x/\max(z_{01}, z_{02})]^{0.8}$
Panofsky and Dutton (1984)	$\delta_i [\ln(\delta_i/z_{02}) - 1] + z_{02} = 1.25 \kappa x$
Jegede and Foken (1999)	$\delta_i = 0.09 (x)^{0.8}$
Savelyev and Taylor (2005)	$\delta_i [\ln(\delta_i/z_{01}) - 1] = 1.25 \kappa x [1 + 0.1 \ln(1/m)]$

590 model by Panofsky and Dutton (1984) shows similar under-prediction beyond
591 $x/\delta \approx 2.5$ for $m = 83.3$ and 125 but shows good agreement throughout the
592 domain for $m = 20$. This model is accurate for $m = 20$ (errors less than 6%)
593 but not for the larger values of m (errors more than 10%). In contrast, the
594 Elliott (1958) model shows overall good agreement for the larger two values
595 of m (errors less than roughly 7%) but shows a significant over-prediction for
596 $m = 20$ (error around 20%). The model by Savelyev and Taylor (2005) shows
597 small over-predictions before, and small under-predictions after, $x/\delta \approx 2.5$
598 for $m = 83.3$ and 125, and small over-predictions throughout the domain for
599 $m = 20$. The error norms are almost always less than 10%, so this model
600 provides reasonable accuracy over a range of m values.

Table 4 Norms of the differences between IBL model predictions and the IBL heights obtained from LES. The IBL heights are calculated based on either the *TSS* (left panel) or the *TI* (right panel) profiles from the LES results

IBL Model	δ_i LES based on <i>TSS</i>			δ_i LES based on <i>TI</i>		
	$m = 20$	$m = 83.3$	$m = 125$	$m = 20$	$m = 83.3$	$m = 125$
Elliot	17.5%	7.6%	7.1%	21.0%	5.8%	6.1%
Wood	14.8%	14.1%	11.3%	11.3%	13.5%	12.7%
Jegede-Foken	15.5%	14.8%	12.0%	12.1%	14.2%	13.4%
Panofsky-Dutton	7.0%	11.8%	10.6%	3.6%	11.2%	12.3%
Savelyev-Taylor	9.5%	8.1%	8.1%	10.8%	6.9%	8.7%

601 3.5 Model for Turbulence Intensity

602 Development of an analytical model for the turbulence intensity downstream
603 of a step change in surface roughness is pursued in this section. To motivate
604 the idea, Fig. 16 shows the *TI* profiles at different distances downstream of the
605 surface roughness jump along with the profile averaged over the upstream por-
606 tion. Further, the gray dashed line in Fig. 16 represents the *TI* profile obtained

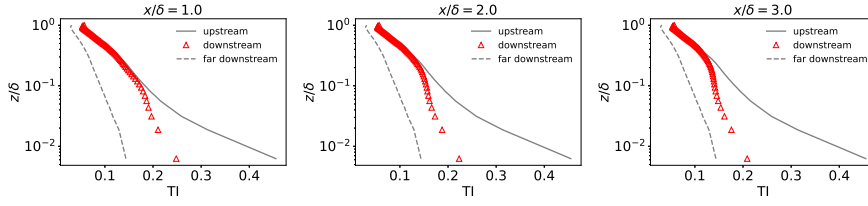


Fig. 16 Vertical profiles of TI at different downstream locations for $m = 83.3$ using the APA wall model compared with profiles in the upstream region and at far-downstream locations on grid G3

607 from a simulation of the flow over a homogeneous surface with roughness z_{02}
 608 (i.e. with the same surface roughness as in the downstream portion of the het-
 609 erogeneous case). This simulation is henceforth denoted as ‘far-downstream’,
 610 since it is expected that at sufficiently far downstream of the roughness jump,
 611 the flow would have adjusted fully to the new surface conditions (roughness
 612 z_{02}) and would have no imprint of the abrupt roughness transition. It is ob-
 613 served that as the downstream distance changes from $x/\delta = 1$ to 3, the TI
 614 profile gradually departs from the upstream profile and approaches the far-
 615 downstream profile.

616 The observation in Fig. 16 that the TI profiles downstream of the roughness
 617 jump are bounded by the upstream and far-downstream TI profiles is utilized
 618 to develop a simple analytical model for the TI . The TI at a downstream
 619 location can be expressed as a weighted average of the upstream and far-
 620 downstream TI profiles,

$$TI(x, z) = \phi TI_{\text{far-downstream}} + (1 - \phi) TI_{\text{upstream}}, \quad (13)$$

621 which can be arranged as

$$\phi(x, z) = \frac{TI(x, z) - TI_{\text{upstream}}(z)}{TI_{\text{far-downstream}}(z) - TI_{\text{upstream}}(z)}. \quad (14)$$

622 In the above equation, TI_{upstream} and $TI_{\text{far-downstream}}$ are not evolving with
 623 the streamwise distance and are functions only of z since they come from
 624 simulations of flow over homogeneously rough surfaces with roughnesses z_{01}
 625 and z_{02} respectively. The empirical, reverse-logarithmic-law model (Stevens
 626 et al. 2018) can be easily used for these two quantities in place of the simulation
 627 results.

628 Figure 17a shows vertical profiles of $\phi(x, z)$ extracted from our LES results
 629 using Eq. 14 at representative downstream locations of $x/\delta = 1, 2$ and 3 for
 630 $m = 83.3$. As expected, ϕ is bounded between 0 and 1. A phenomenological
 631 model is developed for the weighting function considering it to be dependent
 632 on the downstream distance x and the IBL height $\delta_i(x)$,

$$\phi_{\text{MODEL}} = \sqrt{C \frac{\ln(z/\delta_i(x))}{\ln(\delta_e(x)/\delta_i(x))}}, \quad (15)$$

Equation 15 ensures that ϕ_{MODEL} goes to 0 at $z = \delta_i$ and to C at $z = \delta_e$. For the current study a value of $C = 0.8$ is taken. A further correction is required

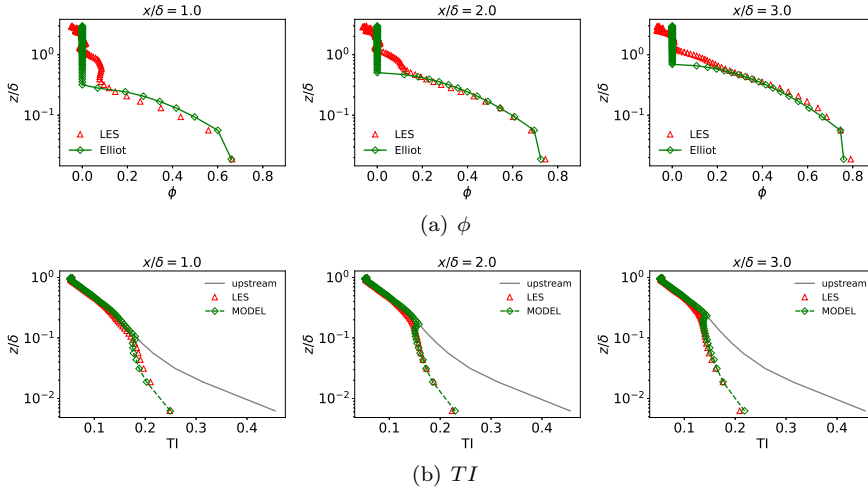


Fig. 17 Comparison of LES results on grid G3 for $m = 83.3$ at different downstream locations of (a) weighting function ϕ and (b) TI to model predictions. Model for ϕ is Eq. 15 and for TI is Eq. 13. In each model, δ_i is obtained using Elliot's relation

at the first vertical point from the wall, as this point is heavily influenced by the wall model in the LES simulations. Equation 15 is multiplied by 0.85 at the first computational point from the wall. To close this model, we use the Elliott (1958) relation for specifying the IBL height and set $\alpha = \delta_e/\delta_i = 0.027$, consistent with the value used for the APA wall model.

Figure 17a shows that this model for ϕ is in fair agreement with the LES results. In particular, the variation of ϕ with height below the IBL height is captured well by the model for all downstream locations. Using this modelled profile for ϕ in Eq. 13 gives a model for TI downstream of a step change in surface roughness.

Comparisons between the LES results and the model predictions are shown in Fig. 17b. It is clear that the proposed model predicts the TI very well at different downstream locations. The modelled TI profile shows a small kink near the top of the IBL, but the agreement with the LES results over the major portion of the domain is very good. The maximum relative error between the LES results and model predictions for TI is 4% close to the top of the IBL.

The model is tested against LES data for other roughness ratios as presented in Fig. 18 at a downstream location of $x/\delta = 3.0$. The profiles of ϕ and TI from the model are seen to be in good agreement with the LES results for these cases as well, indicating that the framework developed here is applicable for a range of surface roughness ratios.

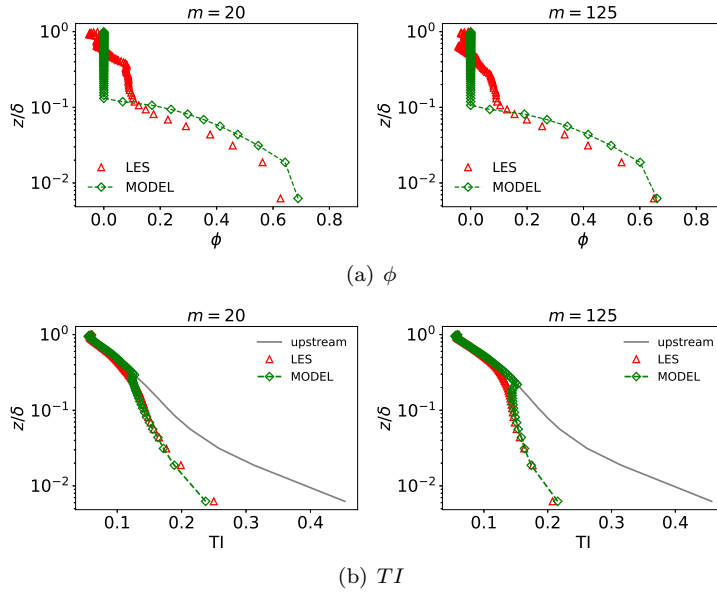


Fig. 18 Comparison of LES results on grid G3 for different values of m at downstream location $x/\delta = 3$ of (a) weighting function ϕ and (b) TI to model predictions. Model for ϕ is Eq. 15 and for TI is Eq. 13. In each model, δ_i is obtained using Elliot's relation

656 Sensitivity of the model for the turbulence intensity to the choice of IBL
 657 height model is shown in Fig. 19. Table 5 shows the maximum relative error
 658 between the TI predicted by model using different IBL models and the LES
 659 results. Using either the Panofsky and Dutton (1984) model or the Savelyev
 660 and Taylor (2005) model for the IBL height leads to fairly good predictions
 661 of the turbulence intensity profiles at different downstream locations for all
 662 three roughness ratios studied here. The kink close to the IBL height is more
 663 pronounced when the IBL height is modelled using the relations proposed
 664 by Panofsky and Dutton (1984) and is smallest on using the Elliott (1958)
 665 relation.

Table 5 Maximum error between the TI at $x/\delta = 3.0$ obtained from LES for different values of m and model predictions of TI using three different IBL models

IBL model	$m = 20$	$m = 83.3$	$m = 125$
Elliot	5.8%	4.0%	5.0%
Panofsky-Dutton	3.9%	8.9%	9.2%
Savelyev-Taylor	3.9%	6.0%	6.9%

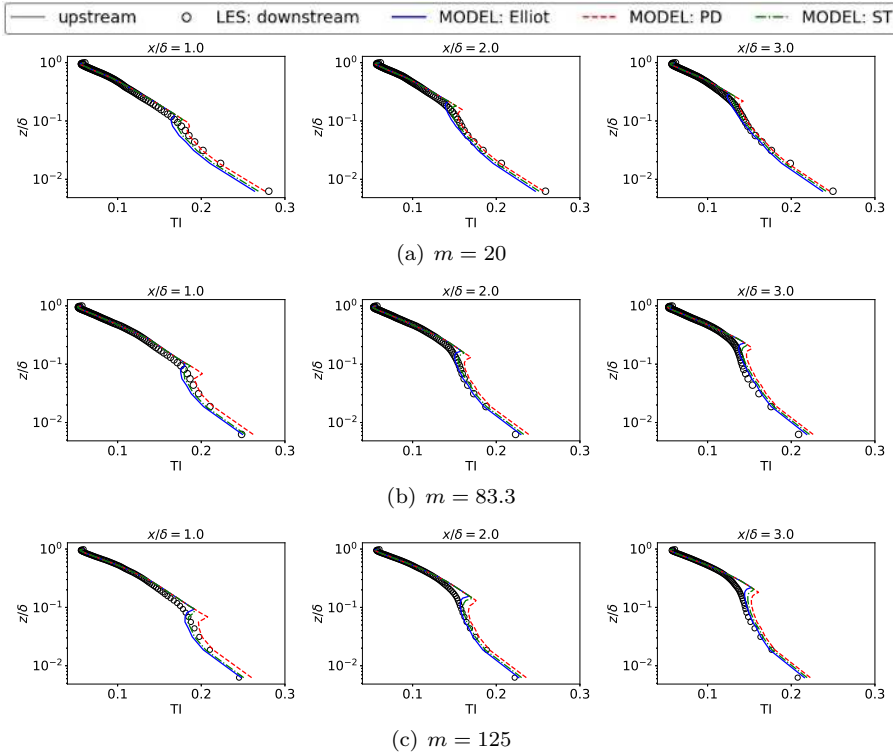


Fig. 19 Comparison of LES results on grid G3 at different downstream locations for (a) $m = 20$, (b) $m = 83.3$ and (c) $m = 125$ of TI to model predictions, Eq. 13, with ϕ given by Eq. 15 and δ_i obtained using three different IBL models, Elliott, Panofsky-Dutton (PD) and Savelyev-Taylor (ST)

666 4 Conclusion

667 The flow over a heterogeneously rough surface, with an abrupt change in the
 668 aerodynamic roughness, is studied here using large eddy simulations. Simu-
 669 lations are carried out using two wall models (BZ and APA), three ratios of
 670 the upstream to downstream roughness ($m = z_{01}/z_{02}$), different grid sizes and
 671 different values of the ratio $\alpha = \delta_e/\delta_i$, which is an input to the APA wall
 672 model. The LES data are compared with appropriate results from the previ-
 673 ously reported wind-tunnel experiments of Chamorro and Porté-Agel (2009)
 674 and Li et al. (2021).

675 Different turbulent statistics of the ABL flow are found to be sensitive to
 676 the wall models to different extents. Specifically, the wall shear stress and tur-
 677 bulence intensity (TI) profile show a large sensitivity to the wall model, with
 678 the APA model giving larger values for both, and being in better agreement
 679 with the experimental results. The mean velocity profile is affected by the wall
 680 model to a lesser extent while the profile of the total shear stress (TSS) is al-

681 most insensitive to the wall model except for very close to the bottom wall.
682 The internal boundary layer height, defined as the height above the bottom
683 surface above which the upstream and downstream profiles are the same, is
684 largely insensitive to the wall model as well as to the quantity (either TSS or
685 TI) used to define it.

686 The LES results on using the APA model are dependent on the ratio, α ,
687 of the equilibrium boundary layer height to the internal boundary layer (IBL)
688 height. Our results show that for the roughness ratios considered herein, the
689 APA model predictions agree well with the experiments when $\alpha = 0.027$, i.e.
690 when the equilibrium boundary layer height is 2.7% of the IBL height.

691 The sensitivity of the flow to changing downstream surface roughness is
692 studied. As the value of m is increased, the downstream surface becomes more
693 smooth and exerts lesser drag force on the flow. This leads to smaller surface
694 shear stresses and turbulence intensities as well as to larger acceleration of
695 the flow close to the wall. The IBL heights calculated based on TSS and TI
696 profiles are found to be independent of the surface roughness ratio. Different
697 analytical models for the IBL height evolution are evaluated. The widely-used
698 Elliott (1958) empirical relation is found to be accurate for higher values of m ,
699 but is found to over-predict the IBL heights for the smallest m studied here.
700 The model proposed by Panofsky and Dutton (1984) is found to be accurate
701 for the smallest m but under-predicts the results for larger m . The Savelyev
702 and Taylor (2005) model is found to be in reasonable agreement with the LES
703 results for the IBL height for all values of m studied here.

704 An analytical model is proposed for the turbulence intensity downstream of
705 the surface roughness jump. This model predicts the TI as a weighted average
706 between the upstream TI profile and the TI profile far downstream of the
707 surface roughness jump. The weighting function, $\phi(x, z)$, is determined by a
708 simple relation and requires the IBL height as an input. Reasonably accurate
709 predictions for the TI are obtained on using any of the three models mentioned
710 above for the IBL height. Nominally, the IBL height given by the Elliott (1958)
711 relation gives good prediction of the turbulence intensity at all downstream
712 locations and for all surface roughness values studied here.

713 The work presented in this paper can be extended along several directions.
714 More experiments and/or wall-resolved LES at surface roughness ratios greater
715 than $m = 83.3$ need to be carried out that will enable development of a
716 methodology of specifying the input α to the APA wall model for these large
717 roughness ratios. The work here focused only on rough-to-smooth transition,
718 and can be extended to smooth-to-rough transitions as well. Finally, studies
719 of surface heterogeneities in the presence of other features, such as a hill, or
720 one or more wind turbines, as well as other configurations of surface roughness
721 heterogeneities can also be carried out.

722 **Acknowledgements** NSG thanks the IIT Hyderabad institute seed grant and SERB
723 Startup Research Grant (SRG/2020/000265) for enabling this work as well as computational
724 resources made available under the National Supercomputing Mission on Param-Brahma at
725 IISER Pune (Grant DST/NSM/R&D_HPC_Applications/2021/28).

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