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1 Does the canopy mixing layer model apply to highly flexible aquatic vegetation? Insights
2 from numerical modelling

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26

27 **Abstract**

28 Vegetation is a characteristic feature of shallow aquatic flows such as rivers, lakes and
29 coastal waters. Flow through and above aquatic vegetation canopies is commonly described
30 using a canopy mixing layer analogy which provides a canonical framework for assessing
31 key hydraulic characteristics such as velocity profiles, large-scale coherent turbulent
32 structures and mixing and transport processes for solutes and sediments. This theory is well
33 developed for the case of semi-rigid terrestrial vegetation and has more recently been applied
34 to the case of aquatic vegetation. However, aquatic vegetation often displays key differences
35 in morphology and biomechanics to terrestrial vegetation due to the different environment it
36 inhabits. Here we investigate the effect of plant morphology and biomechanical properties on
37 flow-vegetation interactions through the application of a coupled LES-Biomechanical model.
38 We present results from two simulations of aquatic vegetated flows: one assuming a semi-
39 rigid canopy and the other a highly flexible canopy and provide a comparison of the
40 associated flow regimes. Our results show that while both cases display canopy mixing
41 layers, there are also clear differences in the shear layer characteristics and turbulent
42 processes between the two, suggesting that the semi-rigid approximation may not provide a
43 complete representation of flow-vegetation interactions.

44 **1. Introduction**

45 Vegetation is a common feature within lowland river environments and influences the
46 functioning of the river system [1]. It acts as an additional source of channel resistance and
47 has been shown to alter bulk flow velocities and conveyance [2-4], generate turbulence
48 through coherent flow structures [5-8], modify sediment transport processes [9-11] and
49 increase habitat diversity [12,13]. Therefore, a good process understanding of boundary layer
50 flow through and around vegetation is central in predicting the functioning of the fluvial
51 system.

52

53 As a result, much research has been conducted into vegetated channels [14]. Our current
54 theoretical understanding of aquatic vegetated flows has been based on our understanding of
55 terrestrial flows through crop fields or forest environments (as reviewed by Finnigan *et al.*
56 [15]). Terrestrial canopy research led to the development of a canonical theory for canopy
57 mixing layers, based upon classical free shear layers, or mixing layers, which has been used
58 to describe flow through and above terrestrial vegetation canopies [16,17] (see section 2).

59

60 As research into aquatic vegetation canopies has subsequently developed, this theory has
61 been transferred and applied to aquatic environments with much of the terminology
62 associated with terrestrial canopy flows being adopted and adapted for aquatic canopy flows
63 [18,7]. However, aquatic canopies inhabit very different physical environments to terrestrial
64 canopies. This will alter the force balance between the flow and vegetation and may
65 substantially modify the dynamics of flow-vegetation interactions. As a result, aquatic
66 canopies display differences in morphology and biomechanical properties. Most notably,
67 submerged aquatic macrophytes are often highly flexible and buoyant, which will affect
68 posture and plant-flow interaction [19]. Thus, in this paper we test the hypothesis that there
69 are fundamental differences between aquatic and terrestrial canopy flow structures.

70

71 We begin by reviewing general canopy layer theory, which applies to terrestrial vegetation
72 and semi-rigid aquatic canopies, before highlighting the potential differences in highly
73 flexible aquatic canopies. We then use an LES-biomechanical model framework [20] to
74 simulate flow through both an idealised semi-rigid terrestrial-style canopy and a highly
75 flexible canopy more typical of those found within rivers. We apply this model in order to
76 capture the high resolution flow dynamics across the length and breadth of the canopy. Using

77 these data, we characterise both flows within a canopy mixing layer framework and compare
78 the predicted and observed canopy flow variables.

79

80 **2. Canopy Mixing Layer Model for Semi-Rigid Canopies**

81 *2.1. Velocity profile*

82 Plant canopies act as a porous blockage [21,22], restricting flow but not preventing it. This
83 porous effect creates two very different velocity regimes: one above and one within the
84 vegetation canopy (U_1 and U_2 in Figure 1). This leads to the formation of a 3-zone velocity
85 profile [23]. The canopy zone is characterised by a region of low longitudinal velocity and
86 also very low longitudinal velocity gradient in the vertical direction [24,6]. The log-law zone
87 above the canopy is unaffected by the additional vegetative drag and therefore the velocity
88 follows the typical logarithmic boundary layer profile [25]. Where these two regions meet,
89 there is an inflection point within the velocity profile and a mixing zone forms, with a
90 hyperbolic tangent curve, or S-shaped velocity profile [16,26,27]. This velocity profile has
91 been observed both in terrestrial [16] and aquatic canopy flows [7,5].

92 *2.2. Turbulence structure and characteristics*

93 The turbulence structure of canopy flows can be split into three distinctive length scales,
94 which correspond to the different velocity profile zones, defined as fine-scale wakes, the
95 active mixing layer and the inactive boundary layer [16]. Fine-scale wake turbulence as a
96 result of stem vortex shedding is a key process within the canopy system, controlling the
97 magnitude of the drag discontinuity between the canopy and the flow above, and in turn
98 affecting the scale of canopy mixing layer turbulence [14]. However, despite its importance
99 as a process in defining canopy scale dynamics, stem-scale wake turbulence accounts for only
100 approximately 10% of the in-canopy turbulence intensity [28]. As it is small-scale in space
101 and time, assuming no backscatter of energy, it will quickly dissipate away into heat [29].
102 Most canopy flows exist within a larger boundary layer, producing large-scale turbulent
103 structures that scale with the depth of the entire boundary layer. This turbulence will interact
104 with the shear-scale eddies but within the canopy it is less likely to impact on the turbulence
105 statistics and is therefore termed ‘inactive turbulence’ [16].

106

107 Instead the active mixing layer turbulence dominates the TKE budget within the canopy [16].
108 These vortices are generated by the Kelvin-Helmholtz (K-H) instability mechanism as a
109 result of the inflected velocity profile of the free shear layer [30,31]. The initial inflection
110 point instability evolves and develops into a series of waves which grow downstream before
111 rolling up into distinct, inclined spanwise roller vortices (Figure 1) [15,32,5]. These vortices
112 expand with distance and time until shear production equals canopy dissipation and the
113 vortex reaches its equilibrium size [32,33,7].

114

115 In between these spanwise rollers, braid regions develop exhibiting high strain rates. Pairs of
116 counter-rotating streamwise rib vortices form in these regions [26] and interact with the roller
117 vortices. Ambient turbulence within the flow then causes pairing of the roller vortices and the
118 interaction between the pair's vorticity fields causes them to converge and rotate around one
119 another [17,5]. This eventually leads to the development of pairs of head-up (H-U) and head-
120 down (H-D) vortices which induce sweep and ejection events.

121

122 This is a key theory as it links two prominent aspects of turbulence research within canopy
123 flows: the development of Kelvin-Helmholtz instabilities and the occurrence of coherent
124 sweep and ejection motions within the canopy. Following Lu and Willmart [34], sweeps (Q4
125 events) are defined as events with larger than average downstream velocity and smaller than
126 average vertical (upward) velocity, and ejections (Q2 events) as events with a smaller than
127 average downstream velocity and a larger than average vertical velocity. It is well
128 documented that within canopy flows, sweeps dominate the canopy region and ejections
129 dominate the flow above [35,36,32,37,24]. It is also recognised that these intermittent, high
130 momentum events are responsible for the majority of energy and momentum transfer between
131 the canopy and the flow above [38,24].

132

133 A number of studies of semi-rigid canopies in both terrestrial and aquatic environments have
134 shown the correlation between sweep and ejection events and the passage of canopy roller
135 vortices [24,39,8,40,23,17]. In contrast to the theory of Finnigan *et al.* [17], who relate sweep
136 and ejection events to hairpin vortex formation, other studies hypothesise that sweep and
137 ejection events simply represent manifestations of vortex passage within the velocity signal
138 [39]. Nevertheless, it is clear that mixing layer vortices and sweep and ejection events are two
139 key observable properties of canopy shear layers and that the two are mechanistically linked.

140 *2.3. Plant response and interaction with the flow*

141 Plant motion in response to the flow can be categorised as one of four regimes. These are
142 erect, gently swaying, honami/monami (coherently waving) and prone [41,6,18,42]. The
143 regime of motion observed for a particular canopy will be determined by the biomechanical
144 properties of the vegetation as well as the drag force [43,32]. While these regimes apply to all
145 canopies, aquatic plants tend to have greater flexibility leading to a greater range of plant
146 motion [6]. The most complex regimes are gently swaying and coherently swaying as these
147 represent dynamic interaction between the flow and canopy. Canopy motion can help absorb
148 momentum from the flow, regulating canopy turbulence [8] and there is also evidence that
149 the natural frequency of the stems can modulate the velocity field and vortex shedding rate
150 [44,45,24,5,46].

151

152 **3. Differences between semi-rigid (terrestrial) and highly flexible (aquatic) vegetation**

153 In the previous section we summarised the influence of vegetation on flow from theoretical
154 work and observations both in terrestrial and aquatic environments. The majority of aquatic
155 canopy layer studies have used vegetation analogous in morphology and biomechanical
156 properties to that used within the terrestrial environment [47,5] or have focussed on aquatic
157 equivalents such as seagrasses [7]. However, aquatic vegetation in rivers exhibits a wide
158 range of forms and can be significantly different to terrestrial vegetation in morphology and
159 dynamical behaviour. Here we suggest that there are three main considerations which must be
160 taken into account when comparing highly flexible aquatic canopies with their terrestrial
161 counterparts.

162 *3.1. Depth-limitation of aquatic flows*

163 Within terrestrial canopies, where the canopy height is small in comparison to the boundary
164 layer height, canopy mixing layer processes interact with the larger scale boundary layer
165 hairpin vortices [17]. Contrastingly, aquatic flows are depth-limited and therefore boundary
166 layer development is restricted and the flow may be dominated by the K-H instability process
167 in the mixing layer [6,48]. Furthermore, vegetation growth is depth-limited through light
168 availability, and therefore deeper aquatic flows where boundary layers may be more
169 significant are less likely to be heavily vegetated [49-51].

170 *3.2. Biomechanical properties and force balance*

171 Within terrestrial environments, plants rely upon rigidity to support their own weight as they
172 grow to compete for light [52]. Conversely, within aquatic environments where the fluid
173 density is 1 000 times greater and therefore the density difference between the plant and the
174 fluid is smaller, rigidity is less important, allowing aquatic plants to be more flexible [53].
175 Furthermore, aquatic species can be positively buoyant [54] and therefore do not rely upon
176 rigidity to compete for light. While rigidity can still be important, particularly for emergent
177 aquatic plants (e.g. *Phragmites spp.*), the majority of macrophytes exhibit low flexural
178 rigidity in response to drag [19,54]. Aquatic plants can experience a drag force 25 times
179 larger than terrestrial plants for a given velocity [55,51]. Therefore, low rigidity enables
180 aquatic plants to reconfigure within the flow to minimize the drag and prevent uprooting or
181 damage [56].

182

183 The differences between the terrestrial and aquatic environments create different force
184 balances. In the semi-rigid terrestrial case, the main forces acting on the stem are the drag
185 (F_D) and the internal rigidity force (F_R), whereas in the highly flexible aquatic case, the main
186 forces are the drag force and the buoyancy force (F_B). These two types of plant may be
187 characterised broadly as ‘bending’ and ‘tensile’ plants [57]. This classification is made on the
188 basis of the Cauchy number (Ca) which is the balance between the drag force and the rigidity
189 force.

$$190 \quad Ca = F_D/F_R \quad (1)$$

191 Nikora [57] categorised plants with large values of Ca as tensile plants and those with small
192 values of Ca as bending plants. Luhar and Nepf [54] extended this approach by characterising
193 the spectrum of vegetation behaviour using both the Cauchy and the Buoyancy number (B).

$$194 \quad B = F_B/F_R \quad (2)$$

195 They used these two parameters and their ratio, which between them represent the ratios
196 between the three key forces, to predict plant reconfiguration. The classification of plant (i.e.
197 bending or tensile) will have an impact upon plant-flow interactions, such as flow modulation
198 by the natural frequency of the vegetation which is likely to be more prevalent in bending
199 canopies.

200 *3.3. Posture and form*

201 As a result of the different force balance, many aquatic plants adopt a horizontal position
202 within the flow, which is a departure from the idealized, perpendicular canopy structure used

203 within terrestrial canopies and many aquatic prototype experiments [58,47]. It is therefore
204 likely that plant-flow interactions will reflect that. Aquatic vegetation must find a balance
205 between drag reduction and photosynthetic capacity [59,60]. Therefore, aquatic vegetation
206 commonly has substantial foliage with a large surface area to maximize light capture. As a
207 result, aquatic vegetation is often characterized by complex plant morphology, which the
208 canopy mixing layer model does not account for. This may be significant in terms of flow
209 structure as foliage can inhibit momentum exchange between the canopy flow and the flow
210 above [61].

211

212 Considering all these factors, flow structure and flow-vegetation interaction within aquatic
213 canopies may be potentially quite different to terrestrial counterparts. However, our
214 theoretical understanding on aquatic vegetation is still firmly based on our process
215 understanding of semi-rigid terrestrial vegetation. Simulating flow through both semi-rigid
216 and highly flexible canopies enables us to assess whether using the theoretical framework
217 generated from work in terrestrial plants is directly transferable to aquatic plants.

218

219 **4. Methods**

220 *4.1. Design of experiments*

221 In order to simulate flow over a canopy, numerical simulations were conducted using a
222 domain 1 m long (l), 0.16 m wide (b) and 0.32 m deep (h) (Figure 2). A canopy of 300 stems
223 was placed within the domain, with a solid volume fraction of $\phi=0.176$ (frontal area per
224 canopy volume, $a=25\text{m}^{-1}$) which represents dense aquatic vegetation and is of a similar order
225 to that used in other canopy studies [62]. Each stem was 0.15 m tall with a radius of 0.005 m,
226 a material density of 950kgm^{-3} and a flexural rigidity of $3.0 \times 10^{-4}\text{Nm}^2$ for the semi-rigid case
227 ($Ca \approx 5, B \approx 0.40$) and $3.0 \times 10^{-8}\text{Nm}^2$ for the highly flexible case ($Ca \approx 50000, B \approx$
228 4000). The stems were positioned in a staggered arrangement (Figure 2). The bed was
229 simulated using a no-slip condition and a logarithmic wall function ($y^+ \approx 20-40$) while, the
230 sidewalls of the domain were simulated as frictionless boundaries to minimise domain-
231 induced wall effects. The free surface was simulated using a rigid-lid treatment. A periodic
232 boundary condition was used at the inlet to allow the full development of a canopy layer
233 profile with a mean domain velocity of 0.3ms^{-1} . The flow was fully turbulent and sub-critical.
234 Flow was simulated for 60s, of which the final 30s of data (approximately 9 flow-throughs)
235 were recorded for analysis.

237 The numerical experiments were conducted within a three-dimensional computational fluid
238 dynamics (CFD) framework within which the Navier-Stokes equations for mass and
239 momentum were coupled and solved using the SIMPLEST algorithm [63]. In this algorithm,
240 an initial pressure field is prescribed which is then used to solve the momentum equations. A
241 pressure correction equation is then applied to ensure continuity. This updated pressure field
242 is then used to solve the momentum equations again and this iterative process is repeated
243 until residual errors are reduced to 0.1% of the inlet flux. A regular Cartesian grid with cell
244 size of 0.002m in each direction was used and the flow was solved using staggered grids for
245 scalar and vector variables. In order to balance the demands of accuracy and stability, a
246 second order, bounded, upwind differencing scheme was used for the convective terms, while
247 central differencing was used for the diffusive terms. The Navier-Stokes equations were
248 solved using Large Eddy Simulation (LES), with a constant Smagorinsky sub-grid scale
249 model ($C_S = 0.17$). The vegetation stems were represented as an immersed boundary within
250 the domain using a dynamic mass flux scaling algorithm [64], whereby individual cell
251 porosities are altered to account for the presence of dynamic mass blockages within the flow
252 without the need for adaptive re-meshing at each time-step [20]. Therefore, in contrast to
253 many LES studies which use fitted grids, with refinement near boundaries, this method
254 represents a low-resolution LES approach, similar to that of Kim and Stoesser [65].
255 Consequently, fine-scale turbulent vortices shed from the individual stems into the wake are
256 not resolved within the model. The impact of this simplification is discussed in Section 5.2.
257 The fluid-structure interaction was solved in a sequentially staggered manner [66], such that
258 velocity and pressure data were passed from the fluid model after each time-step in order to
259 derive plant motion and then new plant position data were fed back into the fluid model for
260 the next time-step. The drag force provided the coupling between the flow and plant models,
261 while other fluid forces were not considered for simplicity. Thus, the effect of the vegetation
262 on flow was incorporated directly through the mass blockage, no slip boundary condition at
263 blocked cell edges and resulting drag force. The corresponding fluid drag force acting on the
264 stems was then calculated from the LES pressure and velocity data interpolated at the stem
265 boundary. The plant position was then solved by balancing the external drag force against the
266 internal inertial and bending stiffness forces [20].

268 To simulate plant motion, two different biomechanical models were applied. These two
 269 models were used to represent the two different vegetation types described in Section 3.2.
 270 The first was based upon the Euler-Bernoulli beam equation and is applicable to semi-rigid,
 271 ‘bending’ vegetation ($Ca \approx O(1), B < O(1)$). Each stem is represented as a cantilever beam
 272 and shear effects are neglected. This type of model has previously been successfully applied
 273 to semi-rigid vegetation canopies [67,68]. The second model is based on an N-pendula
 274 approach and treats each vegetation stem as a series of pendula connected by “hinges” or
 275 “joints”. This model is suitable for modelling highly flexible ‘tensile’ vegetation ($Ca \gg$
 276 $1, B \gg O(1)$) with low rigidity and localised bending. Similar models have previously been
 277 applied to seagrasses [69,19]. Full details concerning the two biomechanical models are
 278 reported by Marjoribanks *et al.* [20].

279 4.4. Analysis methods

280 In order to compare the results within the canopy mixing layer theory framework, four main
 281 analysis methods, which have been used previously to characterise canopy mixing layers [e.g.
 282 7,32,8,70,17] are applied to the data.

283 4.4.1. Normalised velocity and Reynolds stress profiles

284 These are calculated using temporally averaged flow data extracted from the end of the
 285 canopy, spatially averaged across the canopy width ($x/l=0.84$). The variables are normalised
 286 following the approach of Ghisalberti and Nepf [7]. In these equations, U and $\overline{u'w'}$ are both
 287 temporally averaged but are functions of height (z), \bar{U} is defined as the arithmetic mean
 288 velocity of the two flow regions, ΔU is the difference between the mean velocities within the
 289 two flow regions, θ_M is the momentum thickness which is a measure of the thickness of the
 290 shear layer, and \bar{z} is defined such that $U(\bar{z}) = \bar{U}$. These normalised velocity profiles allow
 291 comparison of the data to a conventional mixing layer and can also be used to calculate key
 292 mixing layer variables such as the mixing-layer induced Kelvin-Helmholtz (KH) vortex
 293 frequency (f_{KH}) [31,7].

294

$$295 \quad U^* = \frac{U - \bar{U}}{\Delta U} \quad (3)$$

$$296 \quad \overline{u'w'}^* = \frac{\overline{u'w'}}{\Delta U^2} \quad (4)$$

$$297 \quad \theta_M = \int_{-\infty}^{\infty} \left[\frac{1}{4} - \left(\frac{U - \bar{U}}{\Delta U} \right)^2 \right] dz \quad (5)$$

298
$$z^* = \frac{z-\bar{z}}{\theta_M} \quad (6)$$

299
$$f_{KH} = 0.032 \frac{\bar{U}}{\theta} \quad (7)$$

300

301 The mixing layer velocity profiles are compared to the typical hyperbolic tangent profile of a
302 mixing layer [7]. The Reynolds stress profiles are compared to two previous studies. Firstly,
303 the profile of Rogers and Moser [71], who used direct numerical simulation (DNS) to study
304 plane mixing layers, is used as a comparison to a classical mixing layer theory. Secondly, the
305 results are compared to the theoretical profile developed by Sukhodolov and Sukhodolova
306 [72] for vegetated mixing layers using scaling laws and the turbulent viscosity model.

307 *4.4.2. Spectral and Wavelet analysis*

308 Time series analysis using both a Fourier and wavelet transform is applied for the full
309 duration of the measurement period at a point along the centre line of the domain ($y/b=0.5$) at
310 the downstream end of the canopy ($x/l=0.84$) just above the canopy-top to ensure no
311 interference from stems ($z/h=0.5$). This enables the identification of key periodicities within
312 the flow and is therefore used for assessing the representation of turbulence within the LES
313 model and comparing observed vortex frequencies with those predicted using the canopy
314 mixing layer model (Equation 7). A key advantage of wavelet analysis over other frequency
315 transformations such as spectral analysis is that it retains a temporal dimension which shows
316 how periodicities change through time [73]. The Morlet wavelet is fitted to the data across
317 scales from 0.04 s to 20.48 s, centred at each point in the time series to calculate the wavelet
318 power spectrum. Points that do not have statistically significant wavelet power compared to a
319 white noise spectrum, and those subject to edge effects are discarded and the wavelet scale is
320 converted to the equivalent Fourier period for comparison with other data [20,74]. For the
321 power spectral analysis, the Welch periodogram method was applied to the time series data,
322 with two non-overlapping windows [75].

323 *4.4.3. Quadrant analysis*

324 Quadrant analysis is applied to identify the presence of sweep and ejection events within the
325 flow [34]. Here, downstream (u) and vertical velocity (w) time series extracted from an x - z
326 plane along the midline of the domain ($y/b=0.5$) are decomposed into mean and fluctuating
327 components using Reynolds decomposition. The fluctuating velocities are then plotted onto a
328 quadrant plot which divides the flow into a series of 4 distinct quadrant events: outward

329 interactions, ejections, inward interactions and sweeps [34]. In order to exclude low energy,
330 small-scale fluctuations, a hole-size (H) condition is applied which excludes data where
331 $|u'w'| < Hu_{RMS}w_{RMS}$ with a hole size of $H=2$ [34].

332 *4.4.4. Eulerian and Lagrangian vortex detection methods*

333 To investigate the presence and nature of vortices within the flow, both Eulerian and
334 Lagrangian vortex detection methods are applied. For the Eulerian methods, the Q criterion
335 [76] is used which identifies regions where the magnitude of the vorticity vector is greater
336 than that of the rate of strain. In order to determine the distribution of vortex size, the size of
337 every vortex identified by the Q criterion was measured for an x - z slice down the centre-line
338 of the domain for all time-steps. Only the data above the mean canopy top were used to avoid
339 capturing small-scale and fragmented vortices within the canopy. In addition to the Q
340 criterion, the spanwise component of the vorticity vector is presented, which provides a less
341 stringent condition on vorticity as it is unable to determine between regions of high lateral
342 shear and vorticity [77] but does retain information on the directionality of the vortices.
343 Finally, the Lagrangian analysis applied the Finite-time Lyapunov exponent (FTLE) method,
344 which tracks individual fluid trajectories back through time to identify regions of attracting
345 phase-space [78,79]. This method is limited by fluid trajectories tracking back upstream of
346 the domain inlet, and therefore the time period for tracking trajectories must balance the
347 benefits of increased tracking back period [80] against the size of the region of the domain for
348 which a full trajectory can be calculated. In this case, a track-back period of 0.5s was applied
349 and regions near the inlet without valid trajectories are shown as no data. Vortices are
350 identified as regions of attracting flow with ridges in the FTLE field highlighting the presence
351 of Lagrangian coherent structures [80].

352

353 **5. Results**

354 *5.1. Description of the flow and normalised flow profiles*

355 Instantaneous snapshots of the velocity field (Figure 3) demonstrate that the model captures
356 both stem-scale and canopy shear layer scale flow processes. At the stem-scale (Figure 3a)
357 there is evidence of individual unstable stem wakes leading to the formation of a vortex
358 street. Stem Reynolds number values vary between $Re \approx 300$ -2000 along the stem depending
359 on the local velocity. For the semi-rigid canopy (Figure 3b), the flow quickly develops into a
360 typical canopy shear layer characterised by a sharp velocity gradient at the canopy top, and

361 formation of coherent turbulent structures along the canopy top. For the highly flexible
362 canopy, this shear layer is less well defined and there is evidence of more complex flow
363 structure due to the more prone position of the vegetation and increased plant motion (Figure
364 3c). For example, the canopy height is much more varied than in the semi-rigid case
365 exhibiting large scale streamwise undulations.

366

367 The normalised velocity profiles (Figure 4) show that for both the semi-rigid (SR) and highly
368 flexible (HF) canopies the flow is well described by a mixing layer. This is particularly the
369 case for the highly flexible case which maps closely onto the idealised mixing layer profile.
370 The semi-rigid case shows substantial asymmetry about the centre of the mixing layer with a
371 steep decrease in velocity towards the canopy region ($z^* < 0$). The momentum thickness of
372 the shear layers (θ , Equation 5), calculated from the normalised profiles is 0.021m for the
373 highly flexible case and 0.016m for the semi-rigid case. This suggests that for the highly
374 flexible case the shear layer is thicker. The normalised variables estimate the KH vortex
375 frequencies (Equation 6) for the semi-rigid and highly flexible canopies as 0.52Hz and
376 0.42Hz respectively. While the normalised profiles characterise the flow over the mixing
377 layer regions they do not provide information on the location or dimensional width of the
378 mixing layer. Therefore, the dimensional velocity profiles are also considered (Figure 5).
379 These profiles show the difference between the two cases with a much wider and lower
380 gradient shear layer in the highly flexible canopy case, as compared with the asymmetric,
381 narrow and high velocity gradient mixing layer evident within the semi-rigid case. This
382 highlights the generalising effect of the normalisation process which can remove significant
383 differences in the velocity profiles and is not a sensitive indicator of self-similarity [71].

384

385 The normalised Reynolds stress profiles (Figure 6) provide a more sensitive indicator and
386 show that both the highly flexible and semi-rigid cases have Reynolds stress peaks larger than
387 those typical of a classical mixing layer [71]. The highly flexible profile is similar in shape
388 and magnitude to the theoretical profile derived by Sukhodolov and Sukhodolova [72]
389 ($\gamma = 0.02$) for vegetated mixing layers which also agreed well with their field data. The
390 highly flexible profile also displays a smaller secondary peak below the centre of the mixing
391 layer ($z^* \approx -4$), which may indicate the presence of additional turbulent processes within the
392 canopy due to either plant motion or flow recirculation within the canopy. This secondary
393 peak is $\approx 20\%$ of the mixing layer peak magnitude and is not present within the semi-rigid

394 case. A similar peak is seen in the data of Okamoto and Nezu [8] for a canopy exhibiting
395 *monami*. The semi-rigid profile confirms the asymmetry evident in the velocity profile, with a
396 much steeper decrease in Reynolds stress towards the canopy ($z^* < 0$). The magnitude of the
397 Reynolds stress peak is 50% higher than the highly flexible case and over 200% higher than
398 the classical mixing layer case. This is due in part to the increased velocity difference (ΔU) in
399 the highly flexible canopy, as shown in Figure 5 which in turn decreases the normalised
400 Reynolds stress (Equation 4).

401 5.2. Spectral and Wavelet analysis

402 The velocity power spectra for both simulations (Figure 7a & b) indicate that the turbulence
403 predominantly follows the expected Kolmogorov decay rate, indicating that all the scales of
404 interest lie within the inertial subrange and that the model accurately reproduces the turbulent
405 processes with this range, with minimal impact of numerical diffusion or energy dissipation
406 due to the SGS model [81,82]. As discussed in Section 4.2, fine-scale turbulence at the plant
407 wake-scale is not resolved by the model and therefore experimental data are required to
408 verify the model's performance at such scales where, in similar models, low grid resolution
409 has been shown to result in under-prediction of Reynolds stresses [83]. At larger scales, both
410 flow spectra exhibit peaks close to the predicted KH frequencies (as labelled in Figure 7). In
411 the semi-rigid case, this is a single, well-defined peak. In contrast, for the highly flexible
412 canopy, there is a broader peak, which extends to higher frequencies beyond the predicted
413 KH frequency. The plant motion spectra both display similar peaks to the flow spectra
414 highlighting the coherence between flow and plant motion.

415

416 The wavelet plot for the semi-rigid canopy (Figure 8a) shows a similar pattern to the spectral
417 analysis, with a single dominant periodicity which is initially at the KH frequency predicted
418 from the normalised profiles ($f_{KH} = 0.52$, scale = 1.92s, shown by black line in Figure 8a)
419 but then decreases in frequency and wavelet power in the second half of the simulation. This
420 suggests that local canopy variables may cause the frequency to fluctuate through time. The
421 dominance of the single mixing layer scale periodicity implies that the turbulence regime is
422 controlled by the mixing layer. In contrast, the highly flexible wavelet plot (Figure 8b) shows
423 a larger range of concurrent scales of periodicity as shown by the velocity spectra. There is a
424 clear periodicity at the predicted KH frequency ($f_{KH} = 0.42\text{Hz}$, scale = 2.38s), which as with
425 the semi-rigid case appears to vary through time and is less well defined than in the semi-
426 rigid case. At approximately 15s this periodicity appears to decrease in power and potentially

427 merge with the higher frequency scale before reappearing towards the end of the simulation.
428 There is also a distinct lower scale (higher frequency) periodicity between 1 and 2s (0.5-1Hz)
429 (Figure 8b, dotted line). This signal suggests the presence of additional turbulent processes
430 within the canopy mixing layer region, possibly linked to the secondary peak in the Reynolds
431 stress profile. This scale is greater than that predicted for stem-wake generated turbulence at
432 the canopy top ($f_W = 0.2U/D \approx 6$) and therefore we suggest that this turbulence may relate
433 to plant motion processes. This higher frequency signal contains significant energy with a
434 similar magnitude wavelet power to the mixing layer periodicity, suggesting it contributes
435 substantially to the overall TKE budget. Similar to the lower frequency periodicity, it also
436 shows significant variation in frequency over the duration of simulation. This periodicity
437 agrees well with the velocity power spectra (f_V in Figure 7b) where the turbulence production
438 range extends to frequencies beyond the predicted KH frequency. There is also evidence of a
439 lower frequency, lower power periodicity, which appears to separate from the mixing layer
440 frequency temporarily between 10s and 25s.

441 5.3. *Quadrant analysis*

442 The distribution of high magnitude quadrant events (Figure 9) shows a dominance of sweeps
443 (Q4) within the canopy and a stronger dominance of ejection events above the canopy for
444 both the semi-rigid and highly flexible cases. Within each case, the peak values for sweeps
445 and ejections are similar, with the highly flexible canopy exhibiting a 20-30% increase in
446 occurrence of both. There is also a small peak in sweep events above the mixing layer in both
447 cases. The sweep profiles are similar throughout the flow depth, although the highly flexible
448 case has a higher proportion of sweep events at the top of the canopy (the pattern is reversed
449 for the lower canopy). In contrast, the ejection profiles are less similar, with a larger
450 ‘background’ level of ejection events in the highly flexible canopy, approximately 1-2%
451 higher occurrence than for the semi-rigid case, which extends throughout the flow depth.

452

453 Inward interactions (Q3) show very little variation with height, with a relatively consistent
454 low level (1%) throughout the flow depth, suggesting that the canopy flow regime has very
455 little impact upon these events. Outward interactions (Q1) are prevalent within the canopy for
456 both cases. This has been found in previous studies [36] and attributed to the impact of
457 vegetation motion and the impact of a few large magnitude events penetrating into the low
458 velocity region within the canopy. However, other studies have found no evidence of such a
459 peak in outward interactions [84] and while this may be due to differences in flexibility or in

460 stem density between cases, this remains an area for further work. The contributions of
461 outward and inward interactions diminish towards the canopy top, suggesting increased
462 coherence within the mixing layer [23]. Similar to the sweeps, there appears to be a
463 secondary peak above the mixing layer though the cause of these is unknown.

464 5.4. Vortex detection methods

465 The snapshots of velocity and vorticity within the flow (Figures 10 and 11) provide insight
466 into the instantaneous vorticity field. For the semi-rigid canopy case (Figure 10), the
467 instantaneous velocity streamlines (Figure 10a) highlight the presence of the large-scale
468 coherent structures within the flow. The highest magnitude Reynolds stresses correspond to a
469 structure just above the canopy top ($z/h \sim 0.5$) at approximately $x/l = 0.8$. The vorticity field
470 (Figure 10b) shows the dominance of clockwise (negative) vorticity concentrated along the
471 canopy top and identifies the structure at $x/l = 0.8$ as a clockwise vortex, consistent with a
472 mixing layer roller or possibly hairpin vortex. Above the canopy there are weaker, large-scale
473 vortices which appear stretched in the downstream direction, including the structure
474 identified by the velocity streamlines in Figure 10a, centred at $x/l = 0.4$. The Q criterion
475 (Figure 10c) supports these findings, identifying a small number of large-scale vortices as
476 well as much smaller scale vortices at the canopy top. The FTLE ridges (Figure 10d) also
477 highlight the canopy top as the main region of vorticity, with the clear formation of a roller
478 vortex at the canopy [78]. Marjoribanks *et al.* [20] demonstrated that the growth rate of this
479 roller vortex is consistent with that associated with mixing layer growth.

480

481 The velocity and vorticity plots for the highly flexible canopy (Figure 11a & b) show a more
482 complex distribution of vorticity which extends throughout the full depth of the flow and
483 includes substantial additional regions of anti-clockwise vorticity. Over the duration of the
484 simulation, 64% of the above-canopy domain exhibits positive, anti-clockwise vorticity, in
485 comparison to 41% for the semi-rigid case. There is also evidence of potential vortex
486 shedding from individual stems (as labelled by the arrows in Figure 11). The Reynolds stress
487 patterns (Figure 11a) show greater magnitudes of Reynolds stress within the highly flexible
488 canopy, as compared with the semi-rigid canopy. This appears in contrast to the Reynolds
489 stress profiles (Figure 7). However, as discussed earlier, the normalised Reynolds stress
490 values are scaled by the velocity difference of the shear layer. Therefore, Figure 11a
491 demonstrates that there are high values of Reynolds stress within the flow, but these do not
492 relate to the strength of the shear layer (i.e. they are the result of additional turbulent

493 processes). The Q criterion (Figure 11c) identifies a larger coverage of vortices than in the
494 semi-rigid canopy, and the individual vortices are visually more complex in form. The FTLE
495 results (Figure 11d) highlight vortex ridges extending from the canopy top into the main
496 flow. The pattern is more complex than the semi-rigid case, with more vortex ridges present.
497 The FTLE field also highlights the ridge between counter-rotating vortices which appear to
498 be shed alternately from the canopy top at this instant.

499

500 In order to assess whether these observations generalise throughout the simulation, the vortex
501 size distribution over the entire simulation is assessed statistically. This was calculated by
502 measuring the maximum width in the vertical (z) direction of each vortex at each time-step
503 throughout the duration of the simulation for an x - z slice along the centreline of the model
504 domain. The resulting distribution of vortex diameters (Figure 12), shows that the two cases
505 are broadly similar with an increasing occurrence of vortices with decreasing size, which is
506 expected given turbulence decay processes. The integral length-scale associated with the
507 depth of the flow is 0.32m, however the dense canopy and high shear means that such
508 vortices are unlikely to remain intact. Instead, the integral vortex size scales with the open
509 flow above the canopy (~ 0.17 m). This is demonstrated clearly in Figure 12. The average
510 number of vortices observed at each time-step is similar (SR=21.1, HF=21.81). However,
511 there are noticeable differences in the distribution of vortex size that suggest different
512 turbulent production mechanisms between the flows, occurring at a range of scales.
513 Primarily, the semi-rigid canopy produces more small-scale (<0.02 m) vortices whereas the
514 highly flexible canopy produces more mid-scale vortices (0.02-0.1 m). For the largest
515 vortices (>0.1 m) the distribution is similar between the two cases, with only minor
516 differences. These three regions can be broadly related to different turbulent mechanisms
517 within the flow.

518

519 Firstly, the largest vortices (>0.1 m) correspond to shear layer vortices. This can be seen by
520 examining the distribution of vortex diameter of vortices crossing the location of the time
521 series extracted for the wavelet analysis. For the first 10s of the semi-rigid canopy
522 measurement period, the wavelet spectra (Figure 8a) are dominated by a single low frequency
523 periodicity. The distribution of vortex size at the time series location for this period (Figure
524 13) shows that this larger scale vorticity most likely corresponds to the peak in vortex size
525 between 0.10 and 0.15m. This is supported by the data of Marjoribanks *et al.* [20] who
526 measured a shear-layer generated vortex reaching a width of 0.1m by the end of the canopy.

527 Secondly, we suggest that the difference in distribution of small-scale vortices (<0.02m)
528 relates to additional stem-wake generated vortices. These can be identified in Figure 11b at
529 the canopy top. Assuming Taylor's frozen turbulence hypothesis holds for these small scale
530 vortices, a vortex diameter of 0.02m represents a frequency of approximately 6.25Hz which
531 is consistent with that predicted for the wake shedding mechanism at the canopy top.

532

533 Finally, we hypothesise that the medium-scale vortices relate to additional plant-flapping
534 related turbulence within the highly flexible case. In order to investigate this further we study
535 the relation between vortex size and vorticity for both the highly flexible and semi-rigid
536 canopies. For vortices relating to mixing layer instabilities we expect a dominance of
537 negative (clockwise) vorticity whereas for plant-flapping generated vortex shedding we
538 suggest that the mean vorticity should be zero given that vortices of positive and negative
539 vorticity are alternately shed (Figure 11a). For each vortex scale we analyse the vorticity in
540 the regions defined as vortices according to the Q criterion using two measures: the
541 proportion of vortices with mean positive and negative vorticity and the mean vorticity value.
542 The results (Figure 14) show that the vorticity is very similar between the semi-rigid and
543 highly flexible cases for vortices smaller than 0.07m (small and medium scale vortices). In
544 this region, there is a slight dominance of negative vortices (approximately 60%) with a mean
545 vorticity of between -1.5 and -2s^{-1} . Between 0.07m and 0.11m the trend is also similar, but
546 with a greater dominance of negative vortices and correspondingly a lower mean vorticity of
547 approximately -2.5s^{-1} . We suggest therefore that this may correspond to the most dominant
548 mixing layer scale.

549

550 For vortices greater than 0.11m there is a marked difference in vorticity with an increase in
551 the dominance of negative vorticity for the semi-rigid case and the opposite for the highly
552 flexible case. For the largest scales in the semi-rigid case the flow only consists of negative
553 mixing layer vortices. Here the mean vorticity is approximately -5s^{-1} though this decreases
554 substantially at the very largest scale, suggesting a weakening of vorticity. For the highly
555 flexible case, although the proportion of positive vortices peaks at 90%, the mean vorticity
556 peaks at approximately zero suggesting that the negative vortices are on average nine times
557 stronger at this scale. This general pattern is demonstrated across the vortex diameter scale
558 range suggesting that the mixing layer vortices are the strongest vortices within the flow and
559 that counter-rotating vortices which we suggest relate to plant-flapping, are characterised by
560 weaker vorticity.

561

562 **6. Discussion**

563 The results presented here for both the semi-rigid and highly flexible canopies display typical
564 canopy layer flow characteristics. This demonstrates that shear instability characteristics
565 appear to generalise over a range of plant flexibilities [7,85]. The normalised velocity profiles
566 demonstrate that both canopy flows contain mixing layers associated with inflection points in
567 the velocity profiles just above the canopy. Whilst the velocity profiles both agree with the
568 classical mixing layer profile (particularly the highly flexible case), the Reynolds stress
569 profiles both peak above the value observed for a classical mixing layer. This is in agreement
570 with Sukhodolov and Sukhodolova [72] who found that for a natural vegetation canopy, the
571 Reynolds stress profile was best described by their theoretical profile multiplied by a factor of
572 two. The agreement with this profile observed for the highly flexible canopy (Figure 5)
573 suggests that the highly flexible canopy is representative of the processes occurring in the
574 natural vegetation canopy studied by Sukhodolov and Sukhodolova [72]. For the semi-rigid
575 case, the Reynolds stress profile exhibits an even larger peak, This is in common with the
576 findings of Ghisalberti and Nepf [32] who observed that the magnitude of the Reynolds stress
577 peak increased with stem rigidity, though they observed a lower magnitude peak most likely
578 due to the lower canopy density ($a = 5.2\text{m}^{-1}$).

579

580 The wavelet analysis highlights the presence of mixing layer periodicities in both flows, but
581 also suggests the presence of smaller scale, higher frequency periodicities within the highly
582 flexible canopy flow. These periodicities do not coincide with either the wake-scale or
583 mixing layer scale and therefore most likely relate to other turbulent production mechanisms.
584 This observation agrees with Nikora's [57] model for canopy flows which identifies six
585 distinct turbulence regimes, including boundary layers, mixing layers and wakes across
586 different scales. Of the regimes proposed, some are too large-scale (e.g. depth-scaled
587 boundary layer, vegetated mixing layer) and others too small-scale (leaf-scale boundary
588 layers, stem wakes) to relate to the periodicity observed in the highly flexible canopy.
589 Therefore, we hypothesise that the observed periodicity corresponds to plant flapping induced
590 turbulence. This mechanism cannot be simply described as one of the canonical flow types
591 (e.g. boundary layer, mixing layer, wakes) but is most likely to be caused by a combination
592 of, and interaction between, mixing layer instabilities and wake vortex shedding, similar to a
593 flapping flag [86-88]. It should be noted however that a flapping flag is not the perfect

594 analogue for vegetation stem flapping, due to it being fixed perpendicular to the flow at the
595 bed. This mechanism of turbulence production is of great interest as it is likely to be closely
596 related to plant form and biomechanics and will therefore vary across different plant types.
597 Notably, this turbulence mechanism is not included within the generalised canopy layer
598 model, where vegetation response is treated as an elastic bending response governed by the
599 plant's natural frequency [68,89]. Further research is therefore required to characterise this
600 turbulent process, assess its overall significance and contribution and to include it within the
601 aquatic canopy flow model.

602

603 The absence of this turbulence scale (resulting from plant flapping) in the semi-rigid canopy
604 allows a comparison of its effect in comparison to that of the mixing layer which is present in
605 both cases. The presence of this scale does not dampen the mixing layer signal within the
606 flow, as shown by both the normalised flow profiles and the quadrant analysis. However,
607 there are some unexplained features which may be a result of this additional turbulence scale.
608 The secondary peak in the Reynolds stress profile has previously been observed in canopies
609 exhibiting coherent plant motion [8] and requires further explanation. Similarly, the highly
610 flexible canopy exhibits a greater number of large magnitude ejection events throughout the
611 flow depth. However, there is no corresponding increase in sweep events and therefore it is
612 unclear as to the origin of these events. Finally, the highly flexible canopy exhibited much
613 larger Reynolds stresses over the canopy. These phenomena require further investigation over
614 a wider range of canopy conditions to determine the physical processes responsible for these
615 observations and assess their persistence across a range of canopy densities, stem lengths and
616 rigidities.

617

618 The additional turbulence production within highly flexible canopies has a clear impact on
619 vortex characteristics. However, the impact is not straightforward. Whilst large-scale mixing
620 layer vortices dominate the semi-rigid canopy flow, for the highly flexible canopy flow there
621 exist large-scale vortices with positive (clockwise) vorticity. This suggests that the vortex
622 production by plant-flapping is not restricted to the mid-scale range but also occurs at scales
623 similar to the mixing layer vortices. It is possible that this explains the presence of two very
624 similar low frequency scales within the wavelet plot (Figure 8b) which split and merge
625 through time. Neither the additional vortex occurrence at wake scales within the semi-rigid
626 canopy, nor the additional vortex generation in the mid-scale range in the highly flexible
627 canopy observed in Figure 12 alter the bulk vortex characteristics as demonstrated by the

628 similarity in Figure 14 for scales less than 0.1m. We suggest that this may be due to the fact
629 that both these vortex production mechanisms generate both positive and negative vortices
630 and therefore produce a net zero vorticity. Vortices at these smaller scales are likely to
631 comprise both decaying mixing layer turbulence and additional turbulence production.
632 However, the net vorticity signals of these two processes are likely to be similar. Thus we
633 suggest that it is only mixing layer turbulence processes that significantly alter the vortex
634 characteristics. The exception to this is at the very largest scales in the highly flexible
635 simulation where positive vortices dominate. Here the vorticity is equal to zero suggesting the
636 dominance of stem flapping vortices. However, the proportion of vortices that are positive is
637 approximately 90% rather than the 50% expected from this vortex generation mechanism.

638

639 These results suggest a more complex picture of turbulence production within highly flexible
640 canopies, which retains canopy mixing layer structure, but also exhibits additional turbulence
641 production mechanisms related to stem flexibility. For highly flexible aquatic macrophytes
642 with more complex form and foliage than considered here, we suggest that the role of this
643 plant-flapping scale turbulence may be even further increased. However, the presence of
644 foliage has also been shown to inhibit momentum exchange [61] and we note this as an area
645 for future research. The turbulence generated by this mechanism has been shown to generate
646 large-scale turbulent structures and additional high magnitude turbulent quadrant (Reynolds
647 stress) events. Therefore, we suggest the utility of canopy-layer experiments and models
648 employing semi-rigid or rigid vegetation analogues in drawing conclusions on flow and
649 sediment processes in natural channels with highly flexible vegetation should be carefully
650 considered.

651

652 Future work should be directed at evaluating the observed patterns over a wide range of
653 canopy densities and plant forms. In order to characterise the effect of vegetation with highly
654 complex morphology, as observed in natural environments, further model development is
655 required to increase our capability of modelling fluid-structure interaction with increasing
656 resolution and accuracy. This may involve more strongly couple fluid-structure interaction
657 models, dynamic meshing and more sophisticated turbulence models. In particular, we
658 highlight the need to investigate the fine-scale turbulence processes operating at the wake-
659 scale and the effect these may have on larger scale turbulence dynamics through turbulent
660 backscatter. Nevertheless, we suggest that the methodology applied here provides a useful
661 approach for characterising flow-vegetation interactions.

663 **7. Conclusion**

664 This paper presents results from numerical simulations of flow through two canopies: one
 665 semi-rigid and one highly flexible. Two different models were employed to capture the
 666 dynamics of each canopy based upon their characterisation as ‘bending’ and ‘tensile’
 667 canopies respectively. These models were applied to similar flow conditions in order to
 668 evaluate their agreement with canopy flow theory. The main conclusions of this study are:

- 669 1. The fundamentals of canopy flow generalise across a wide range of vegetation
 670 rigidities. This includes the mixing layer flow profile, vortex generation and
 671 occurrence of turbulent sweep and ejection events.
- 672 2. However, highly flexible canopies exhibit evidence of additional turbulent processes
 673 at scales that are different to those expected for mixing layers and other known
 674 turbulent processes (e.g. boundary layers and wakes)
- 675 3. These processes are most likely related to plant-flapping induced turbulence. Other
 676 than through elastic-response, such plant-related turbulent processes have not been
 677 extensively studied, but may contribute a hereto unrecognised influence on flow and
 678 channel processes in aquatic environments.

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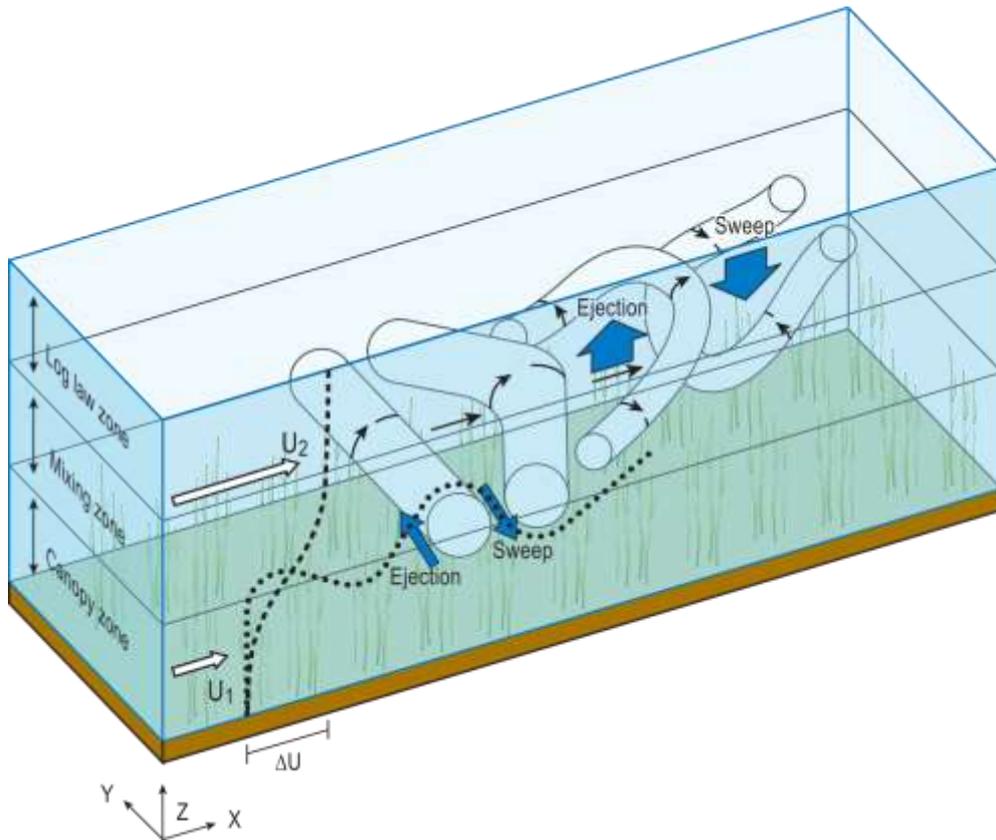
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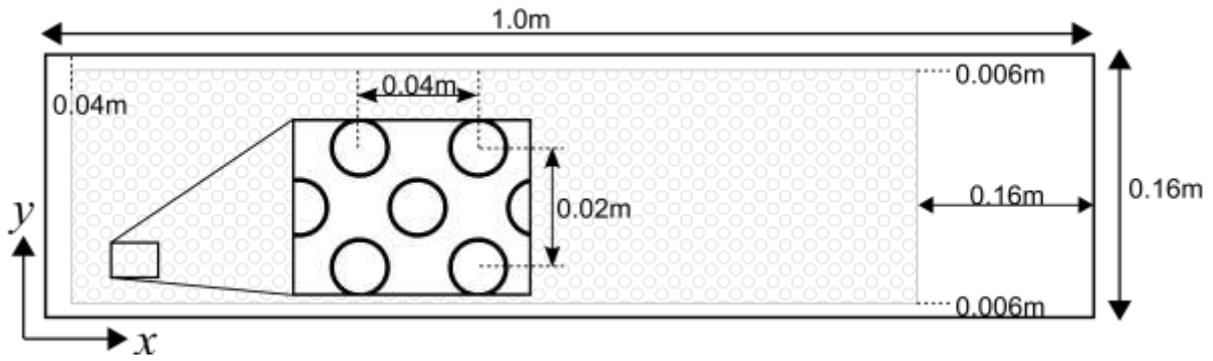
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901 **Fig. 1** Schematic model of canopy flow. The difference between the velocity within (U_1) and
 902 above (U_2) the canopy leads to the development of an inflected velocity profile (dashed line).
 903 This velocity profile can be split into 3 zones: i) the canopy zone, ii) the mixing zone and iii)
 904 the log law zone. At the inflection point, Kelvin-Helmholtz instabilities form (dotted line)
 905 which develop into roller vortices which are convected downstream along the canopy top.
 906 These vortices are stretched and form pairs of head up (H-U) and head down (H-D) hairpin
 907 vortices which induce ejection and sweep events respectively (blue arrows). Sweep and
 908 ejection events have also been linked to the passage of the roller vortices (blue arrows).

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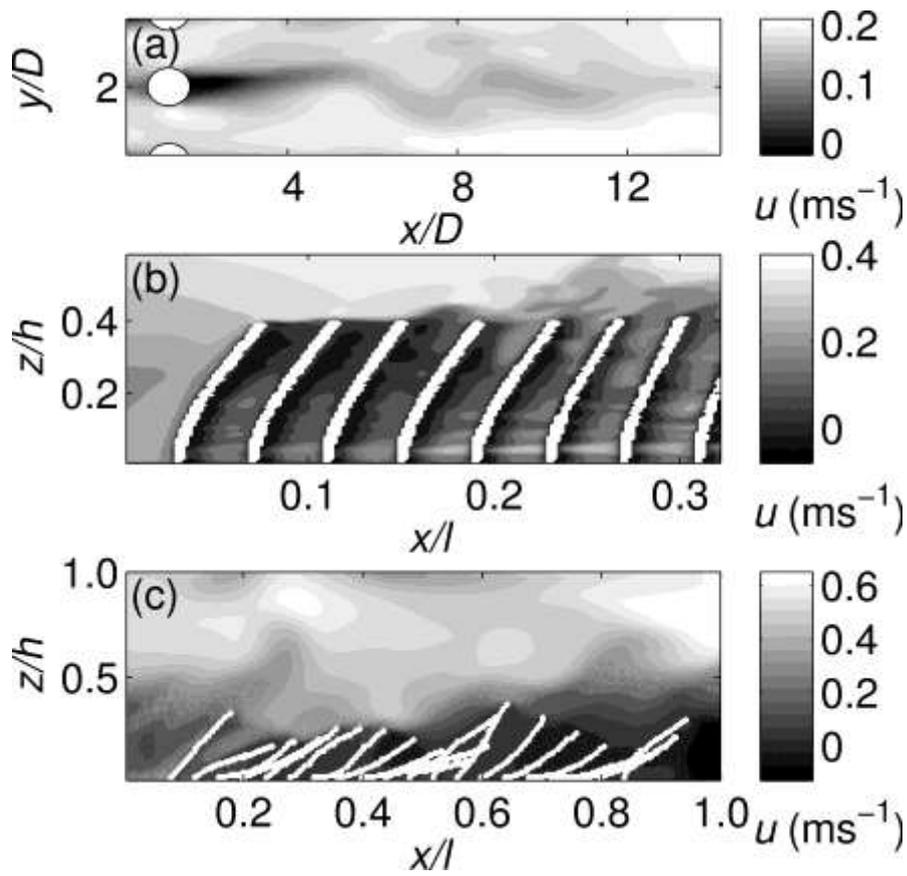
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912 **Fig. 2** Plan view schematic of the simulation setup with flow from left to right with the

913 vegetation canopy shown by the shaded region. Domain not drawn to scale.

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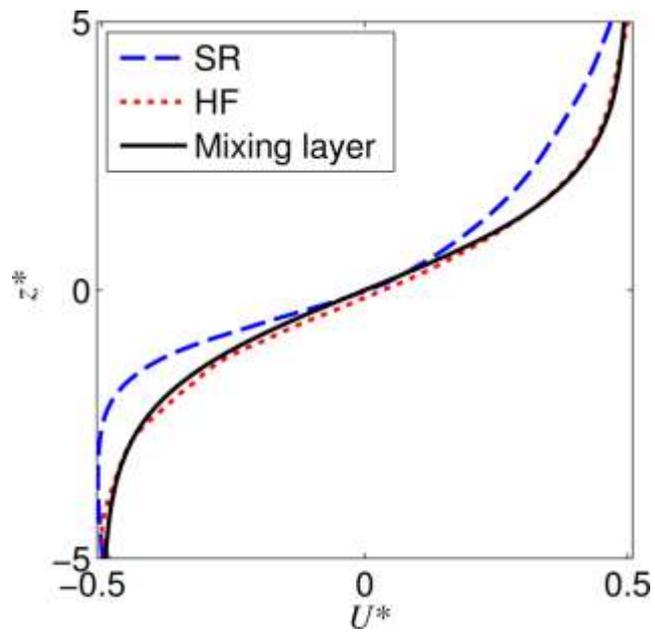
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916 **Fig. 3** Instantaneous snapshots of (a) wake flow, (b) shear flow and (c) the entire domain.

917 Subfigures (b) and (c) demonstrate typical plant positions for the semi-rigid and highly-

918 flexible canopies respectively. Flow is from left to right

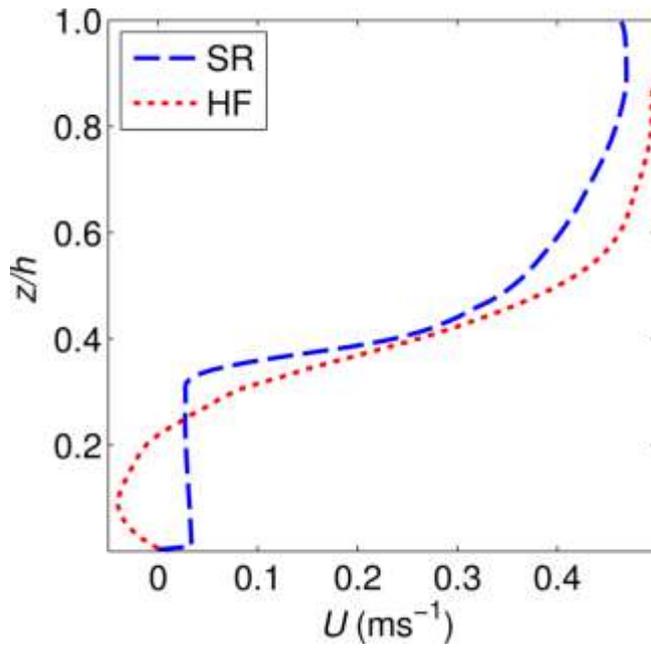
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921 **Fig. 4** Normalised velocity profiles for the semi-rigid (SR) and highly flexible (HF) canopies,
 922 as well as the idealised mixing layer profile as used by Ghisalberti and Nepf [7].

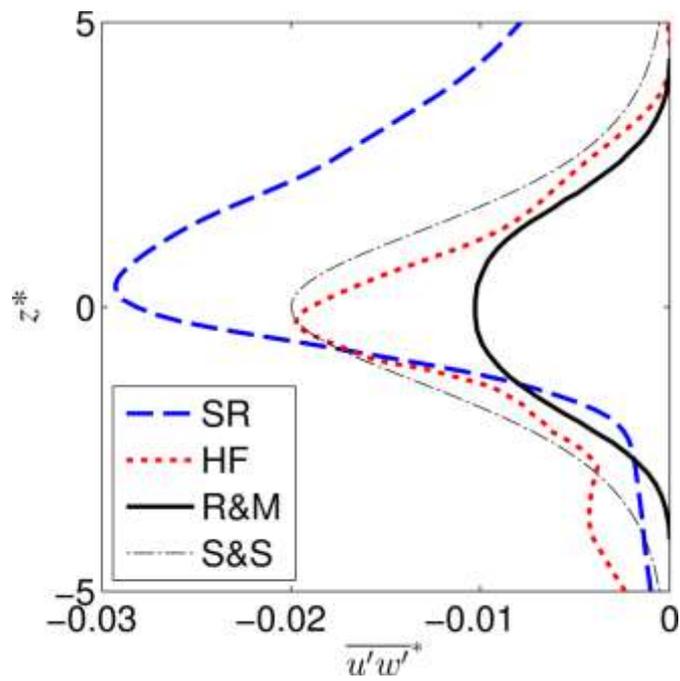
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925 **Fig. 5** Downstream velocity profiles for the semi-rigid (SR) and highly flexible (HF)
926 canopies.

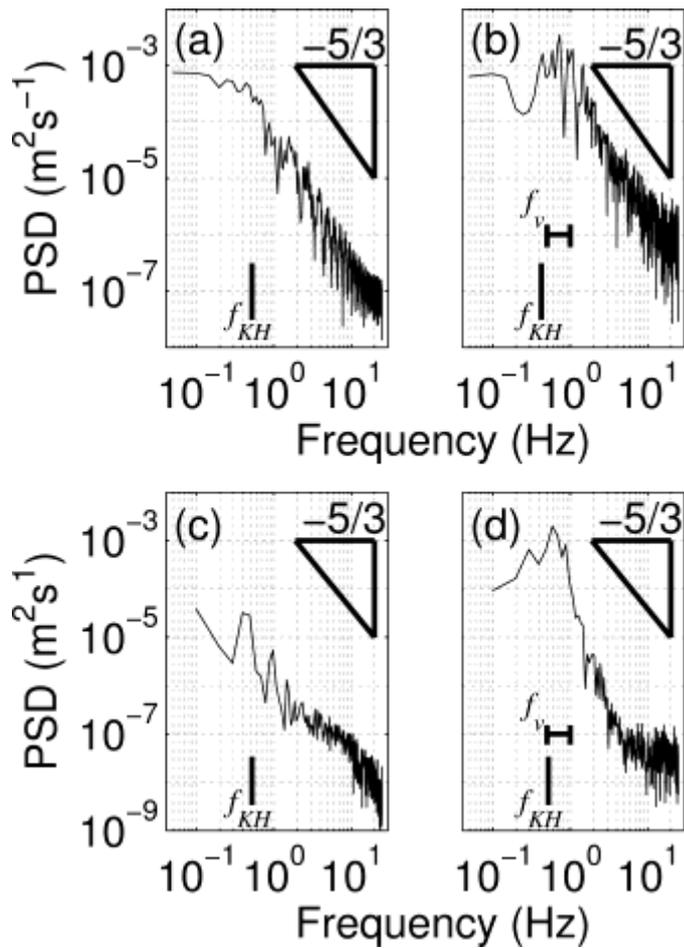
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930 **Fig. 6** Normalised Reynolds stress profiles for the semi-rigid (SR) and highly flexible (HF)
 931 canopies. The experimental mixing layer profile of Rogers and Moser [71] (R&M) and the
 932 theoretical canopy profile of Sukhodolov and Sukhodolova [72] (S&S) are also shown.

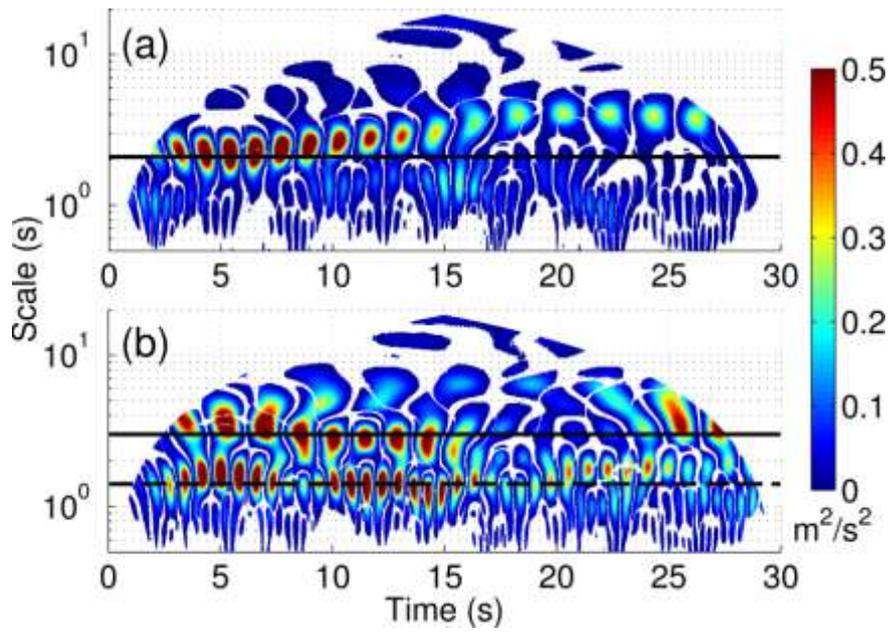
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935 **Fig. 7** Power spectra for the velocity (a & b) and stem height (c & d) time series for the semi-
 936 rigid (a & c) and highly flexible (b & d) canopies. The Kolmogorov -5/3 scale is shown by
 937 the triangle while the lines represent the scales corresponding to the predicted K-H (f_{KH}) and
 938 vegetation-induced (f_v) frequencies.

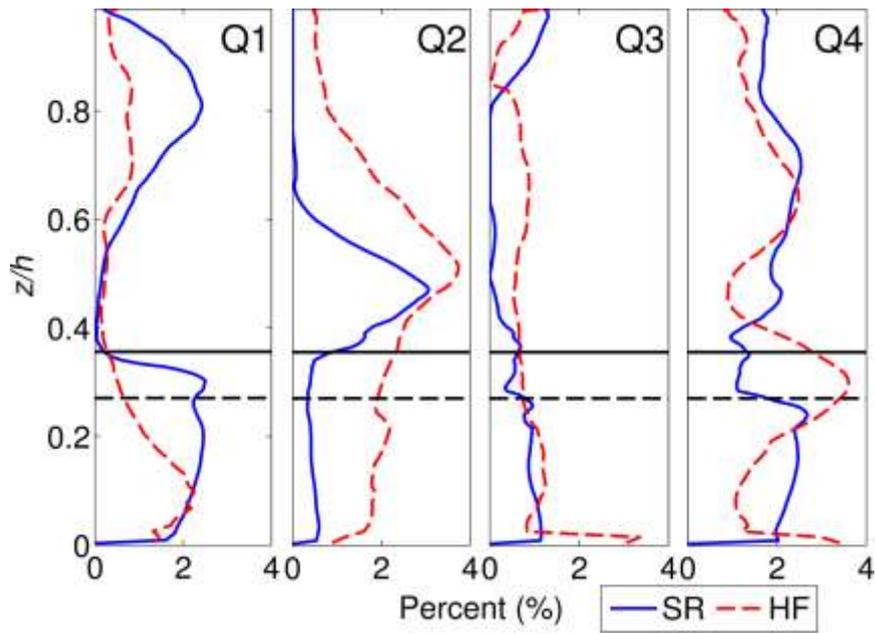
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941 **Fig. 8** Wavelet spectra for the semi-rigid (a) and highly flexible (b) canopies. The black lines
942 indicate the predicted KH vortex frequencies.

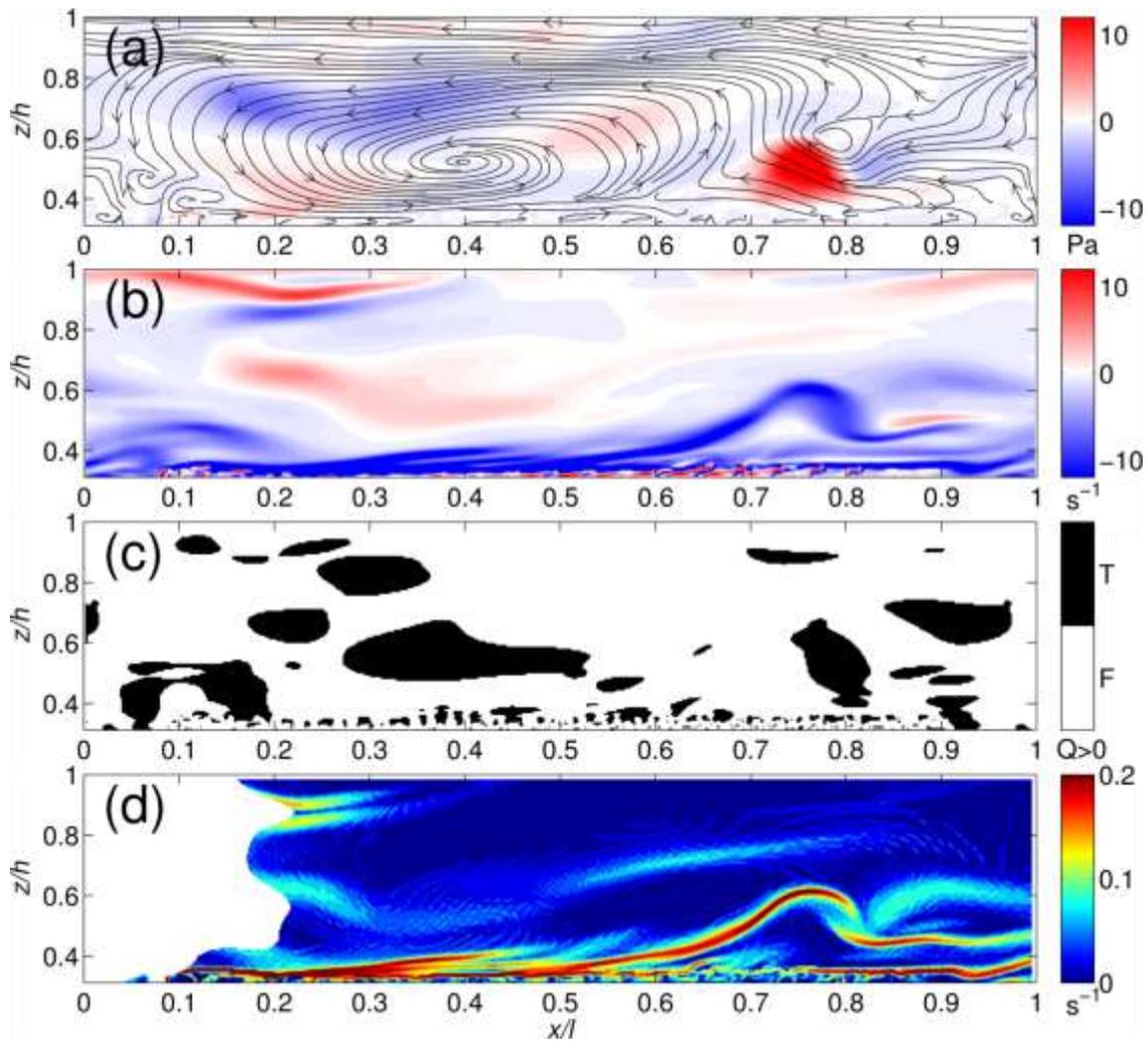
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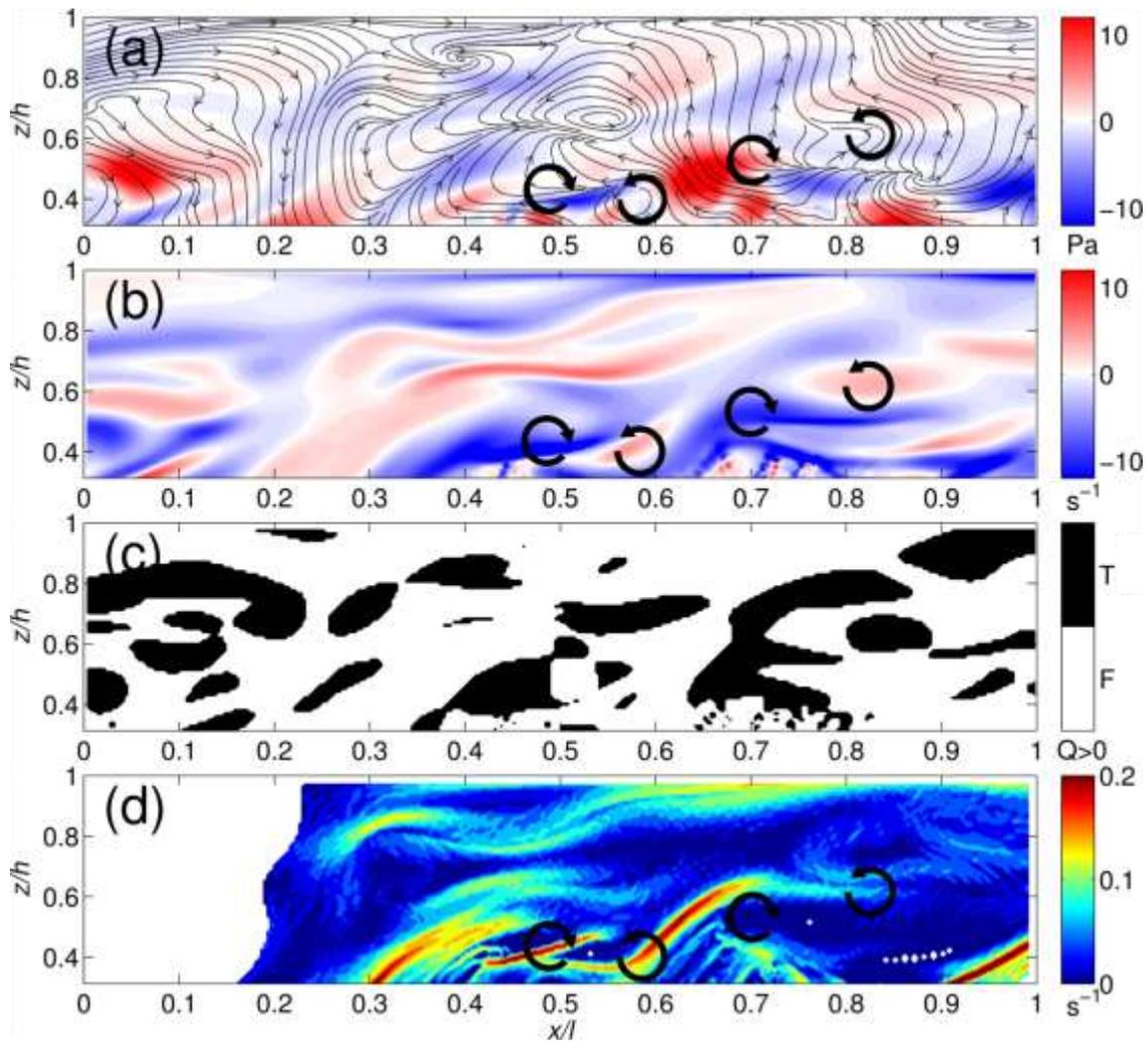
945 **Fig. 9** Quadrant profiles for the semi-rigid (SR) and highly flexible (HF) showing the vertical
 946 distribution of high energy quadrant events ($H=2$). Approximate canopy heights are shown by
 947 the black lines for the SR (solid) and HF (dashed) cases.

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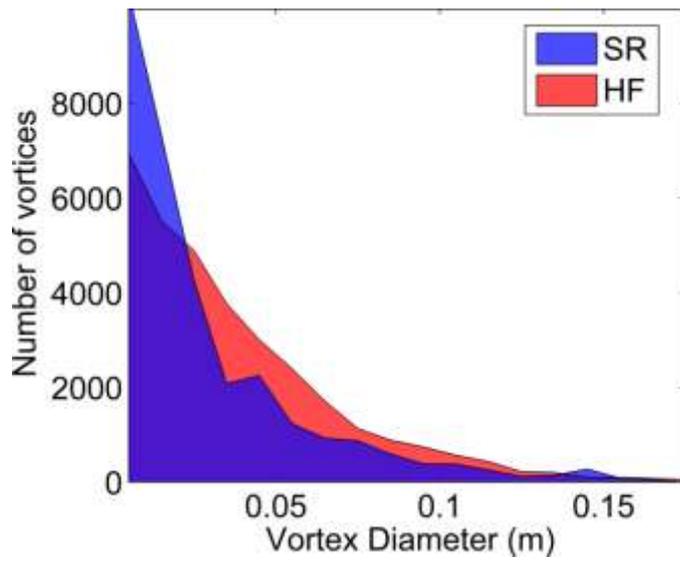
950 **Fig. 10** Vortex identification for the semi-rigid canopy using (a) Reynolds stress (contours)
 951 and instantaneous velocities (streamlines) (b) vorticity, (c) Q criterion and (d) FTLE methods.
 952 Flow is from left to right and for clarity, only flow above the canopy is shown. The mean
 953 canopy height is at $0.35z/h$



954

955 **Fig. 11** Vortex identification for the highly flexible canopy using (a) Reynolds stress
 956 (contours) and instantaneous velocities (streamlines) (b) vorticity, (c) Q criterion and (d)
 957 FTLE methods. Flow is from left to right and for clarity, only flow above the canopy is
 958 shown. Black arrows highlight the presence of potentially plant-shed vortices. The mean
 959 canopy height is at $0.27z/h$.

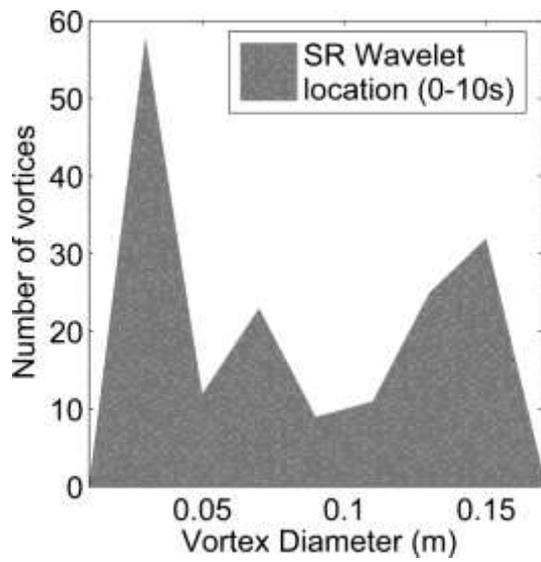
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962 **Fig. 12** Occurrence of different sized vortices throughout a 2D x - z slice of the domain for the
963 duration of the simulation for the semi-rigid (SR) and highly flexible (HF) canopies.

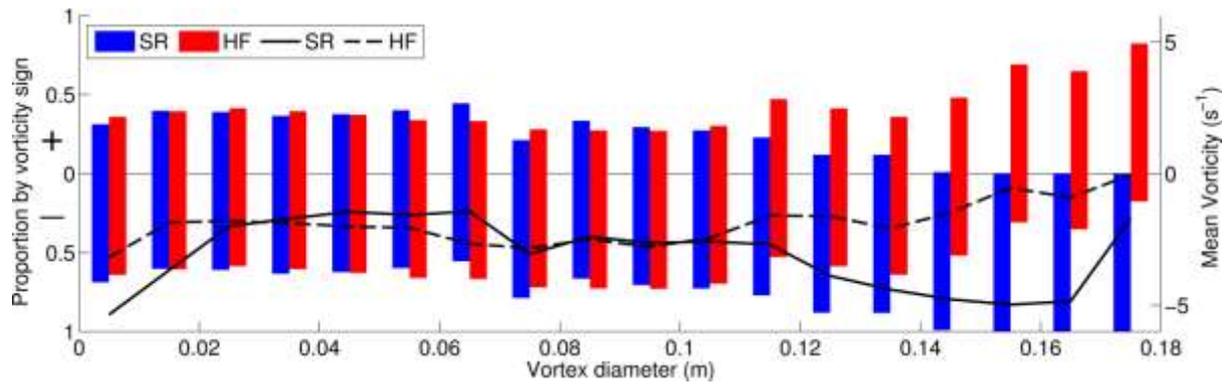
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966 **Fig. 13** Occurrence of different sized vortices at the location of the time series extracted for
967 the wavelet analysis during the first 10s of the semi-rigid canopy simulation.

968



969

970 **Fig. 14** Distribution of vortex sign (rotation direction) and mean vorticity with vortex
 971 diameter. Positive sign corresponds to anti-clockwise rotation and negative sign to clockwise
 972 rotation. The bars demonstrate the proportion of vortices of each sign for the semi-rigid
 973 (blue) and highly flexible (red) canopies. The lines plot the mean vorticity for each vortex
 974 size class, for the semi-rigid (solid) and highly flexible (dotted) canopies.