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1 **Modelling canopy flows over complex terrain**

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3 **Gardiner**

4

5 Draft: 31st July 2015

6 **Abstract** Recent studies of flow over forested hills have been motivated by a num-
7 ber of important applications including understanding CO₂ and other gaseous fluxes
8 over forests in complex terrain, predicting wind damage from trees and modelling
9 wind energy potential at forested sites. Current modelling studies have focused al-
10 most exclusively on highly idealised, and usually fully forested, hills. This paper
11 presents model results for a site on the Isle of Arran, Scotland with complex terrain
12 and a heterogeneous forest canopy. The model uses an explicit representation of the

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13 canopy and a one-and-a-half order turbulence closure for the turbulence within and
14 above the canopy. The validity of the turbulence closure scheme is assessed using
15 the turbulence data from the field experiment before comparing predictions of the
16 full model with the field observations. For near-neutral stability the results compare
17 well with the observations showing that a relatively simple canopy model such as this
18 can accurately reproduce the flow patterns observed with complex terrain and realis-
19 tic variable forest cover, while at the same time remaining computationally feasible
20 for real case studies. The model allows a closer examination of the flow separation
21 observed over complex forested terrain. Comparison with model simulations using a
22 roughness length parametrization show significant differences, particularly with re-
23 spect to flow separation and this highlights the need to explicitly model the forest
24 canopy if detailed predictions of the near-surface flow around forests are required.

25 **Keywords** Complex terrain, First order mixing length closure, Flow separation,
26 Forest canopy, Numerical modelling

27 **1 Introduction**

28 There has been significant interest over the last few years in modelling the effects
29 of canopy flow over complex terrain. This has been motivated by a number of is-
30 sues, particularly the need to understand and interpret CO₂ flux measurements over
31 complex forested sites, where advective effects can lead to a significant difference
32 between above-canopy fluxes and the source / sinks within the canopy (Katul et al.,
33 2006; Ross and Harman, 2015). Other important applications include assessing wind
34 damage to trees and estimating potential wind energy resources for wind farms. Real-

35 world sites tend to be complicated, in terms of both the terrain and heterogeneity in
36 the forest canopy. In contrast the vast majority of modelling studies so far have ad-
37 dressed highly idealised problems. Many concentrate on flat, homogeneous canopies
38 (e.g. Pinard and Wilson, 2001). Where they do study heterogeneous problems, these
39 are often highly idealised such as a sharp forest edge (Liu et al., 1996; Yang et al.,
40 2006; Dupont and Brunet, 2008, 2009; Dupont et al., 2011; Banerjee et al., 2013;
41 Schlegel et al., 2015) or idealised fully forested hills (Ross and Vosper, 2005; Ross,
42 2008; Dupont et al., 2008; Patton and Katul, 2009). The recent paper of Ross and
43 Baker (2013) takes this slightly further by looking at partially forested (but still ide-
44 alised) hills. There are good reasons for starting with such idealised problems. It
45 allows for a systematic study of the individual processes influencing flow over for-
46 est hills. These problems may also be amenable to analytical analysis (e.g. Finnigan
47 and Belcher, 2004). It is also possible to reproduce some of these problems in the
48 laboratory (e.g. Poggi and Katul, 2007) to provide validation data for the models.
49 However, ultimately we need to be able to model flow over real, complex terrain with
50 complicated, heterogeneous forest cover. This study aims to do that. The simulations
51 discussed here are based on the field experiment described in Grant et al. (2015) and
52 the field observations will be used to validate the modelling. The aim is to assess the
53 feasibility of using existing models to tackle such complex problems and to investi-
54 gate some of the issues faced when making such realistic simulations.

55 There are currently two principal approaches used for modelling turbulence in
56 canopy flows: mixing length closure schemes (e.g. Pinard and Wilson, 2001; Ross and
57 Vosper, 2005; Banerjee et al., 2013) and large-eddy simulations (LES) (e.g. Brown

58 et al., 2001; Yang et al., 2006; Ross, 2008; Dupont et al., 2008; Patton and Katul,
59 2009). LES offers advantages in terms of requiring fewer assumptions about the na-
60 ture of the turbulence in forest canopies, but the excessive computational demands
61 make it usually impractical in terms of modelling realistic cases over large domains,
62 although Schlegel et al. (2015) have demonstrated that this is possible, at least for
63 idealised flow across a forest edge with a real heterogeneous canopy structure. Pre-
64 vious work has shown that while there are limitations in its applicability, mixing
65 length closure schemes actually perform reasonably well in terms of predicting mean
66 flow over relatively flat, homogeneous canopies from both a theoretical (Finnigan
67 and Belcher, 2004) and a practical (Pinard and Wilson, 2001) perspective. In a recent
68 paper Finnigan et al. (2015) have reviewed the applicability and limitations of mixing
69 length closure schemes from a theoretical perspective. In this study we will look at
70 how applicable such schemes are for modelling more complex terrain and heteroge-
71 neous forest canopies in reality, using the one-and-a-half order mixing length closure
72 scheme from Ross and Vosper (2005).

73 In section 2 the model setup is described. Section 3 provides some validation
74 for the mixing length closure by testing the closure assumptions using observational
75 data over complex terrain from Grant et al. (2015). Section 4 presents a comparison
76 of the model and observational results in terms of the mean flow, momentum fluxes
77 and turbulent kinetic energy. The sensitivity of the model to the parametrization of the
78 surface is investigated in Section 5, and the model results are used to better understand
79 the complicated flow separation over a realistic site. Finally section 6 provides some
80 discussion and conclusions.

2 Description of observations and model

The case study used in this paper comes from a field experiment conducted on the Isle of Arran, Scotland during spring 2007. The experiment is described in detail in Grant et al. (2015). The field site is the ridge Leac Gharbh which is situated on the north-east coast of Arran. The ridge is orientated north-west / south-east with the southern end of the ridge being mostly covered with Sitka spruce and mixed deciduous trees. Here we make use of wind speed and direction measurements made from a network of 12 automatic weather stations (AWS) and 3 instrumented towers as described in Grant et al. (2015). The AWS were fitted with cup anemometers and wind vanes at 2m height and were located both within and outside the forest canopy. The 3 towers varied in height from 15 to 23m with 4 sonic anemometers mounted on each. The towers formed a transect across the forested part of the ridge. The data presented is based on 15-minute average wind speeds and directions. The choice of coordinate system for sonic anemometer measurements in complex, forested terrain is non-trivial, as highlighted by a number of recent studies including Ross and Grant (2015); Oldroyd et al. (2015), however for simplicity and for consistency in comparing with the model, a double rotation into streamwise coordinates is carried out here, as in Grant et al. (2015). This coordinate system means u is the velocity component in the streamwise direction, w is the slope normal velocity component and v is the remaining velocity component in the axis perpendicular to u and w .

Given the uncertainty in the forest parameters and in the upstream flow conditions, and also the local variability in the observations, this study aims to model some generic flow conditions (neutral flow with a 10 ms^{-1} geostrophic wind and different

104 fixed geostrophic wind directions) and compare them with the observational clima-
105 tology, rather than trying to precisely model particular case studies. The focus here
106 is on near-neutral flow for a couple of reasons. Firstly, much of the previous theoret-
107 ical work (e.g. Finnigan and Belcher, 2004; Ross and Vosper, 2005; Ross and Baker,
108 2013) is for neutral flow, and one motivation of the paper is to test how these ideas
109 can be applied to more complex terrain and canopy cover. Secondly, under stable
110 conditions canopy flows are known to decouple, with an in-canopy drainage flow dis-
111 tinct from the above canopy flow (see e.g. Belcher et al., 2012). This is an important
112 problem, but the mixing length closure model described here has not been developed
113 or tested with such flows in mind, and so for this study such regimes are excluded.

114 Numerical simulations were conducted using the BLASIUS model, originally de-
115 veloped at the UK Met Office and described in Wood and Mason (1993). The model
116 solves the three-dimensional, time-dependent Boussinesq equations of motion in a
117 terrain-following coordinate system. The addition of a canopy drag term and a mod-
118 ified turbulence scheme (see Ross and Vosper, 2005) make it suitable for modelling
119 canopy flows over hills. It has been used for studying a range of idealised problems
120 related to canopy-covered hills (Brown et al., 2001; Ross and Vosper, 2005; Ross,
121 2008, 2011; Ross and Harman, 2015), partially forested hills (Ross and Baker, 2013)
122 and variable canopy densities (Ross, 2012). The model has been validated against
123 wind tunnel measurements over a hill, and against observations from a flat hetero-
124 geneous forest (Ross and Vosper, 2005), but this is the first time the model has been
125 applied to such complex, heterogeneous terrain as this.

126 The simulations described here use a one-and-a-half order mixing length closure
 127 scheme with a prognostic equation for the turbulent kinetic energy, k . The scheme
 128 is described in Ross and Vosper (2005), however in summary the eddy viscosity is
 129 calculated as $\nu_t = \Gamma_0^{1/2} k^{1/2} l_m$ where Γ_0 is the (assumed constant) ratio between the
 130 stress and the energy and l_m is the mixing length, which is constant within the canopy
 131 and scales with height above the canopy. In BLASIUS a default value of $\Gamma_0 = 0.357$
 132 is used. The turbulent kinetic energy satisfies

$$\rho \frac{Dk}{Dt} = \rho \nabla \cdot (\nu_t \nabla k) + \tau_{ij} \frac{\partial U_i}{\partial x_j} - \rho \epsilon \quad (1)$$

133 where ρ is the density of the air, U_i is the mean wind speed, τ_{ij} is the Reynolds stress
 134 tensor and ϵ is the dissipation. The Reynolds stress is modelled as $\tau_{ij} \equiv -\rho \overline{u'_i u'_j} =$
 135 $\rho \nu_t S_{ij}$ where $S_{ij} = \partial U_i / \partial x_j + \partial U_j / \partial x_i$ is the deformation tensor. To close the prog-
 136 nostic equation for turbulent kinetic energy requires the dissipation term, ϵ to be
 137 parametrized. This takes the standard form above the canopy ($\epsilon_{cc} = k^{3/2} \Gamma_0^{3/2} / l_m$),
 138 with an enhanced dissipation $\epsilon_{fd} = Ca |\mathbf{U}| k$ within the canopy (following Wilson
 139 et al., 1998) to account for canopy drag rapidly converting energy from large scales
 140 to small, quickly dissipated “wake scales”. The overall dissipation within the canopy
 141 is taken as the maximum of these two terms $\epsilon = \max(\epsilon_{cc}, \epsilon_{fd})$. See also Katul et al.
 142 (2004) for a useful discussion of k and $k - \epsilon$ models applied to canopy flows.

143 Terrain and land use data (50m horizontal resolution) came from the Ordnance
 144 Survey Landranger and MasterMap products, accessed via EDINA (2011). The model
 145 domain was $6\text{km} \times 6\text{km}$ with 120 grid points in each direction giving a horizontal
 146 resolution of 50m. The domain is centred on the Leac Gharbh ridge. The height of
 147 the domain was 5km with a stretched vertical grid of 80 points giving a vertical res-

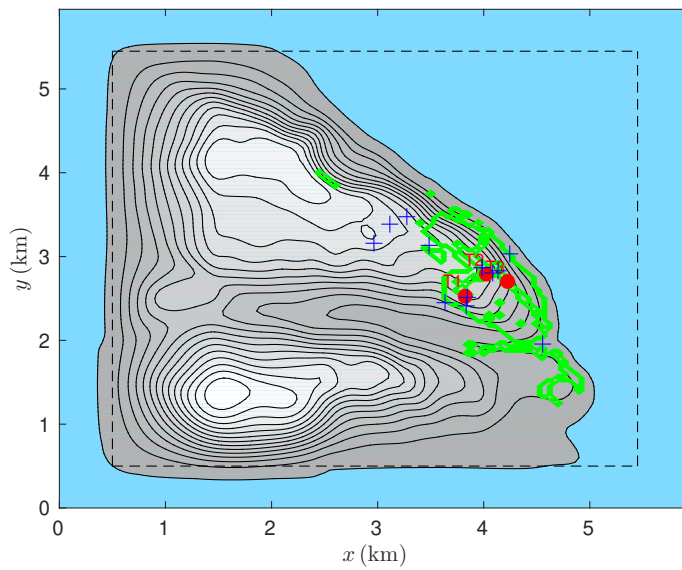


Fig. 1 The model domain used in the BLASIUS simulations. The shaded grey colour denotes the terrain height, with contours every 25m. The solid green line marks the boundary of the forest. The red circles labelled T1-T3 denote the 3 instrument towers and the blue + show the location of the AWS. The light blue area around the edges denotes sea, where a lower roughness length z_0 is used. The dashed line marks the edge of the damping layer.

148 olution varying from 0.5m at the surface to approximately 180m at the top of the
 149 domain. In order to keep the model domain to a computationally manageable size
 150 lateral periodic boundary conditions were used, with a damping layer applied over
 151 the outermost 500m of the domain to relax the solution back towards the geostrophic
 152 wind profile. The terrain is also smoothed to zero in the damping layer domain and
 153 the surface roughness set to the value over the sea to ensure continuity across the
 154 periodic boundaries. Figure 1 shows the model domain and illustrates the topography
 155 and forest cover used. The white area around the edges and to the top right is sea.

156 The location of regions of different land use is accurately obtained from the Ord-
157 nance Survey data, however there is significant uncertainty in the correct roughness
158 length and canopy parameters to use in these regions. Field measurements of tree
159 properties made by Forest Research near the field site (Grant et al., 2015) suggest that
160 a canopy height $h = 15$ m, uniform canopy density of $0.5 \text{ m}^2 \text{ m}^{-3}$ and canopy drag co-
161 efficient $C_d = 0.25$ are broadly representative of the forest cover on the ridge. There
162 is variation in the canopy cover, however given the lack of detailed measurements
163 across the whole ridge and the other uncertainties in the modelling, these represen-
164 tative canopy parameters should be reasonable. The roughness length used over the
165 land outside the forest and at the forest canopy floor is 0.05 m, representative of grass-
166 land. Over the sea a lower representative value of 0.005 m is used. The sensitivity of
167 the results to these roughness lengths will be assessed later. The model simulations
168 were all run to steady state (approx 1000s or twice the domain advection time).

169 3 Validation of mixing length closure

170 Typically turbulence closure schemes are validated using data from relatively flat,
171 homogeneous sites (e.g. Pinard and Wilson, 2001). To test the validity of the tur-
172 bulence closure assumptions in BLASIUS over a site with complex, heterogeneous
173 terrain observational data from the field campaign described in Grant et al. (2015)
174 is analysed. The one-and-a-half order turbulence scheme in BLASIUS assumes that
175 the Reynolds stress tensor τ_{ij} is given by $\tau_{ij} = -\rho \overline{u'_i u'_j} = \rho \nu_t S_{ij}$. Even in complex
176 canopy flows scaling analysis suggests that the stress tensor S_{ij} is usually dominated
177 by the vertical gradients of the horizontal velocity components, and so here we focus

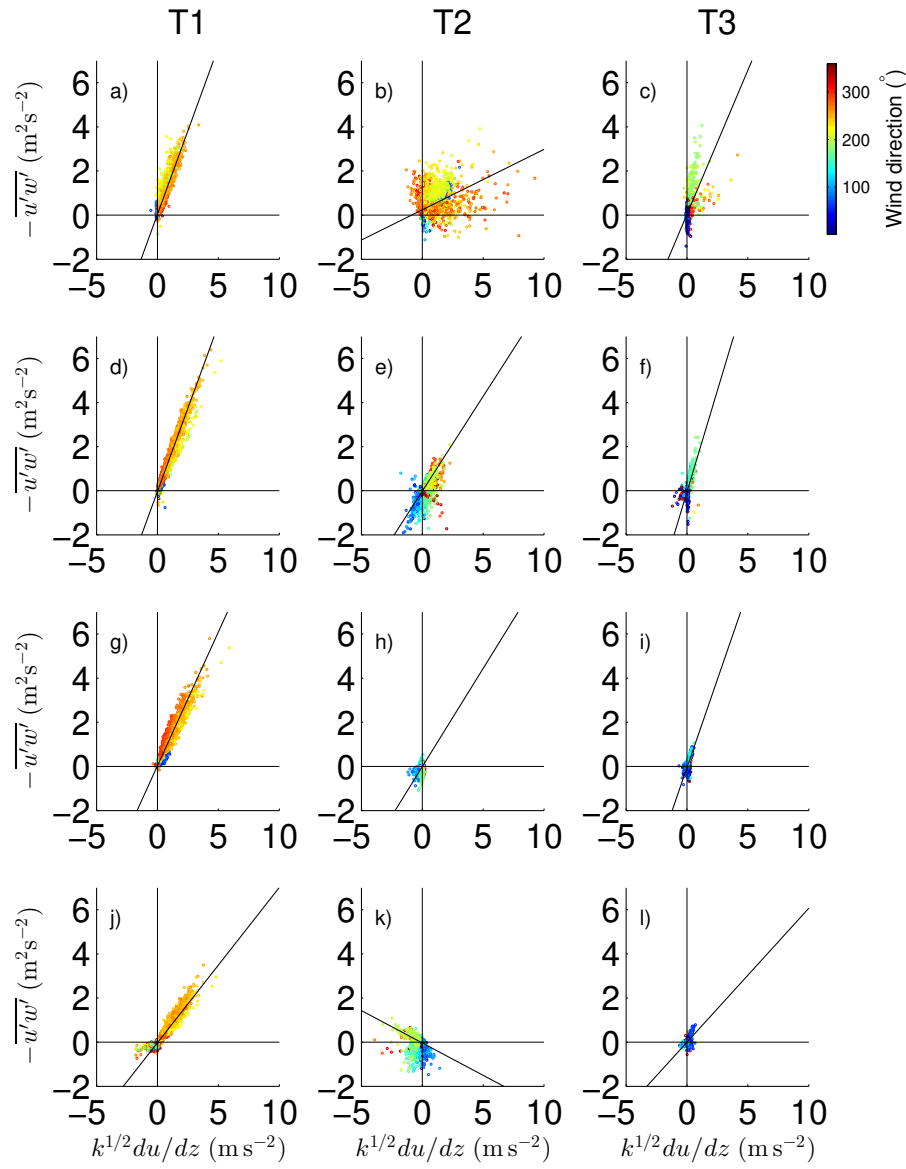


Fig. 2 Momentum flux $\overline{u'w'}$ in streamwise coordinates as a function of $k^{1/2}\partial\overline{u}/\partial z$ where k is the turbulent kinetic energy. The colours denote the direction of the mean wind for each 15-minute averaged data point. The solid line is a best fit line to the data which passes through the origin. The slope of the line is proportional to the mixing length l_m . The three columns correspond to towers T1 (left), T2 (centre) and T3 (right). The rows correspond to the different heights on each tower with the top row corresponding to the top of the tower, and the bottom row the lowest instrument height.

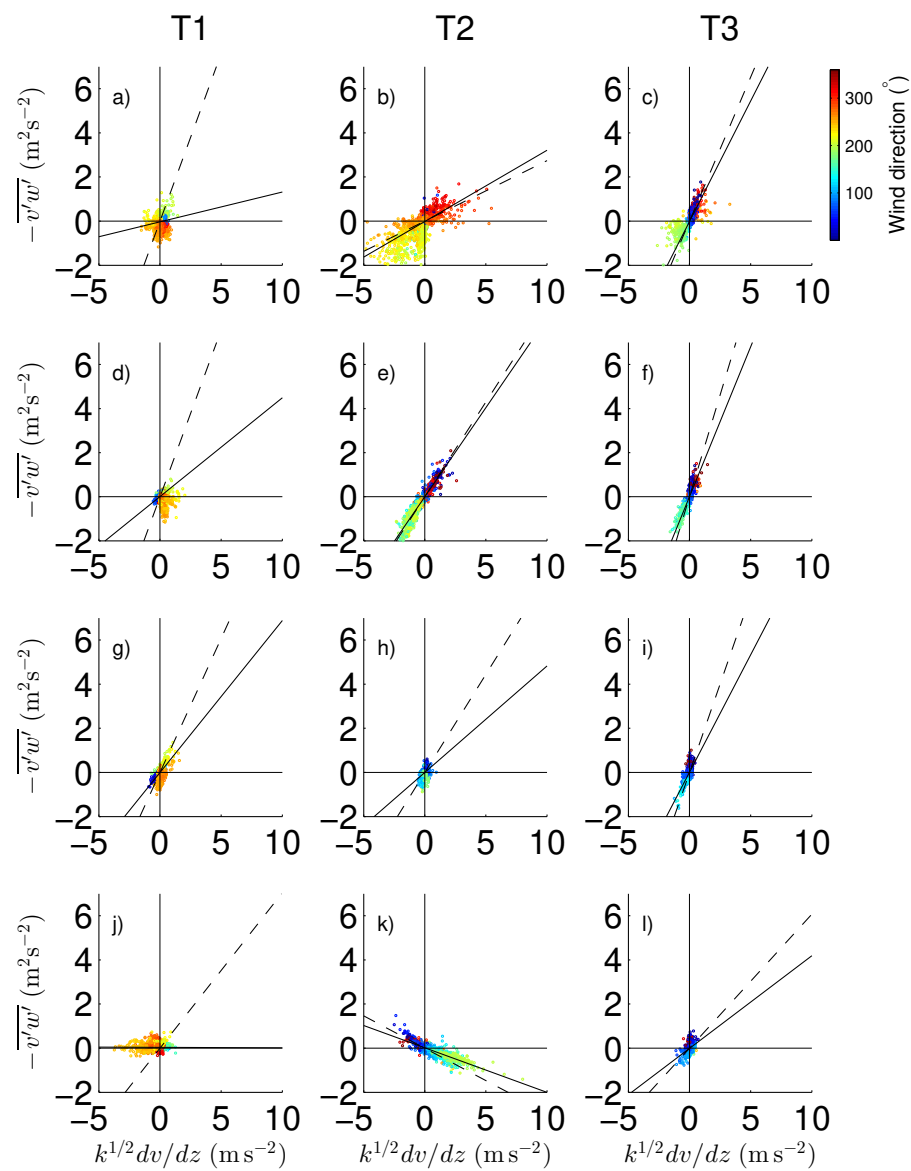


Fig. 3 As for Fig 2, but for $\overline{v'w'}$ as a function of $k^{1/2} \partial \bar{v} / \partial z$. The dotted line shows the slope of the equivalent subplot in Fig 2.

178 on $-\overline{u'w'} \approx \Gamma_0^{1/2} l_m k^{1/2} \partial u / \partial z$ and $-\overline{v'w'} \approx \Gamma_0^{1/2} l_m k^{1/2} \partial v / \partial z$. The vertical gradients
 179 in streamwise coordinate are calculated by first rotating into a fixed frame of refer-
 180 ence relative to the ground, calculating the gradients at the midpoints between the
 181 observations by finite differencing, linearly interpolating the results back onto the
 182 measurement heights and then finally rotating back into the local streamwise coordi-
 183 nates at each height. Here quality controlled data from Grant et al. (2015) for all wind
 184 directions and stabilities is used to assess the validity of the closure assumptions. The
 185 quality control involves ensuring sufficient data is available in each 15-minute aver-
 186 aging period and also that the data passes the stationarity test of Foken and Wichura
 187 (1996) as described in Grant et al. (2015). This quality controlled data amounts to
 188 about 4000 data points for T1, 3600 data points for T2 and 2500 data points for T3.

189 Figure 2 shows the momentum flux, $-\overline{u'w'}$, plotted against $k^{1/2} du/dz$ for the 3
 190 turbulence towers (T1, T2 and T3) situated across the ridge. The linear best fit line
 191 through the data is also plotted. The slope of this line is proportional to the average
 192 mixing length, l_m with the constant of proportionality being $\Gamma_0^{1/2}$. The results show
 193 that for tower T1 the data collapses well, with the mixing length relatively constant
 194 with height within the canopy (the best fit line has the same slope at different heights).
 195 There is some slight evidence of a decreased mixing length at the lowest height due
 196 to the close proximity to the ground. Similar plots of $\overline{v'w'}$ against $k^{1/2} dv/dz$ in Fig. 3
 197 show a relatively small vertical flux of across-stream momentum, suggesting little
 198 directional shear and an approximately two-dimensional flow.

199 In contrast to tower T1, at tower T2, which is surrounded on nearly all sides by
 200 trees and where there is often flow separation at the lower two levels, the collapse of

201 the data is far less good. The fluxes are generally lower, and there is significant direc-
202 tional wind shear in the vertical (see Grant et al., 2015, for details). This directional
203 shear is not observed at tower T1 and may be responsible for the poorer data collapse
204 at tower T2. Interestingly there does seem to be a dependence on the mean wind di-
205 rection, which is most noticeable at the top of T2. For particular wind directions (e.g.
206 easterly winds) the data does seem to collapse, but the slope is a function of the wind
207 direction. For other wind directions (e.g. northerly / north-westerly winds) there is
208 no clear collapse. This may suggest that the mixing length is dependent on the flow
209 direction. This would make sense since it is the upwind forest canopy density which
210 will control the observed mixing length. At the second height down on T2 there is
211 a much stronger linear relationship, but the sign of the flux exhibits a strong depen-
212 dence on the wind direction. The negative values of $\overline{u'w'}$ are at first glance surprising
213 given the wind speed typically increases with height at this location. Due to the strong
214 direction wind shear however du/dz is actually negative. It is not clear why the data
215 collapse is better at the second height down than at the top of T1, although it might be
216 related to the proximity of the top of the tower to canopy top, or to difficulties in accu-
217 rately calculating the shear in this region. The strong directional wind shear at the the
218 second height down might also result in a stronger correlation between the local shear
219 and the local turbulent momentum fluxes. A further complication is the presence of a
220 SW-NE aligned fire break across the ridge just to the south of T2 which may impact
221 on the flow for certain wind directions. It is not clear though that the data collapse
222 is worse for cases where the wind is blowing from this direction. At the lowest two
223 measurement heights, in the region of separated flow and where the speeds are low-

224 est, there is little evidence of any linear relationship between $\overline{u'w'}$ and $k^{1/2}d\overline{u}/dz$. At
 225 the lowest height, the apparent trend is negative, which is contrary to the underlying
 226 assumptions in the closure model and suggests either a non-local source for the tur-
 227 bulent eddies responsible for the momentum transport or errors in the calculation of
 228 the wind shear at this location. The scatter however is large and so the relationship is
 229 not clear. The plots of $\overline{v'w'}$ against dv/dz show that the cross-stream momentum flux
 230 is not insignificant at this site (again, consistent with the importance of directional
 231 shear). The first order closure still seems to hold reasonably well, particularly at the
 232 second height from the top of the mast. The slopes of the solid and dashed lines are
 233 very similar showing that the mixing lengths inferred from $\overline{v'w'}$ are very similar to
 234 those derived from $\overline{u'w'}$, which is again encouraging. At the lowest height, as for $\overline{u'w'}$,
 235 the data collapses surprisingly well but gives a negative slope. The other noticeable
 236 feature at tower T2 is that the sign of the shear term $k^{1/2}dv/dz$ is strongly dependent
 237 on wind direction suggesting two different flow regimes for broadly north-easterly
 238 and broadly south-westerly flow, which is again consistent with the profiles given in
 239 Grant et al. (2015) and with the plots of $k^{1/2}du/dz$.

240 T3 is taller than T1 and T2, and so the top measurements are above the canopy.
 241 Despite this the data collapse is less clear. For much of the time and for certain wind
 242 directions the data does lie on a straight line, however again during periods of flow
 243 separation there is often a positive value of $\overline{u'w'}$, indicative of the effects of direc-
 244 tional shear. The diagnosed mixing lengths are relatively constant with height, similar
 245 to those at tower T1. The plots of $\overline{v'w'}$ show a similar collapse of the data to those of
 246 $\overline{u'w'}$ and very similar mixing lengths. Values of $\overline{v'w'}$ lie somewhere between those at

247 towers T1 and T2, suggesting that direction shear may be important here, but proba-
248 bly less than at tower T2. The data at the lower heights collapses well, but as for $\overline{u'w'}$
249 there is a directional dependence on the mixing length at the top of the tower.

250 Calculating an average mixing length from the slope of the best-fit line using only
251 data with $\overline{u'w'} < 0$ gives fairly consistent results, with mixing lengths in the range of
252 2.3 – 3 m at most heights on towers T1 and T3, and lower values close to 1.5 m at
253 the lowest instrument heights. These mixing length values are surprising consistent
254 with values derived from the plots of $\overline{v'w'}$, particularly at towers T2 and T3 where
255 the directional shear and cross-stream momentum flux are most important. The data
256 from the top of tower T3 remains somewhat different and is separated into two flow
257 regimes. The bulk of the data, for broadly easterly winds with no flow separation, lies
258 on the steeper line with a slope giving $l_m \approx 4.8$ m. This tower is taller than towers T1
259 and T2 and the instrument is well above the height of the canopy, so one would expect
260 to see an increase in the mixing length at this location under these conditions. The
261 remaining data is predominantly for westerly cases with flow separation and stronger
262 directional shear and is characterised by larger values of the shear term $k^{1/2} du/dz$ but
263 weaker momentum fluxes. Mixing length closure schemes are known to have issues
264 in separated flows (e.g. Ross et al., 2004) and so it is perhaps not surprising that a
265 different behaviour is observed in this separated flow regime.

266 From all these profiles one can conclude that in many cases (particularly where
267 there is little directional shear) a mixing length closure assumption is reasonable,
268 and that the diagnosed mixing lengths from the observations are consistent with the
269 common assumptions of a constant mixing length in the canopy. Only at T3 do mea-

270 surements extend much above the canopy, and these seem to suggest a mixing length
271 which increases with height (at least for non-separated flow), although there are not
272 enough measurements to conclude whether this relationship is linear with height as
273 expected from theory. This has important implications for the numerical modelling
274 of canopy flows in complex terrain. There remain a number of cases (particularly at
275 T2 near the summit) where there is flow separation and strong directional shear, and
276 in these cases the mixing length closure assumptions do not appear to hold as well.
277 Some cases with directional shear (e.g. the 2nd height from the top on tower T2) do
278 actually support the assumption of a constant mixing length, and so it may be that it is
279 not the directional shear *per se* which is important, but the fact that the mixing length
280 is strongly dependent on the wind direction due to very different upstream conditions
281 in different directions. For many of the cases where the simple mixing length closure
282 assumptions do not hold the corresponding momentum fluxes are small anyway, and
283 so the overall impact on the mean flow may not be significant. There is also more
284 uncertainty associated with the observations in the cases with significant directional
285 shear. Weak mean flow and larger directional shear make it harder to calculate the
286 gradient terms du/dz in the mean flow in a robust manner. Weak mean winds also
287 lead to more variability in the calculated streamwise coordinate rotations, which may
288 impact on the calculated momentum fluxes. Both of these are likely to increase the
289 scatter in the results as for example is observed in the plots of $\overline{u'w'}$ from the lower
290 two instruments on T2 (Figs. 2(h) and (k)) located deep within the canopy. Over-
291 all these results support the use of the one-and-a-half order mixing length closure
292 scheme implemented in the BLASIUS model. The precise impact the regions of di-

293 rectional shear, and the associated errors in the mixing length turbulence closure,
294 have on model predictions of mean flow fields will be investigated in the following
295 section by comparing results from the full model with the observations.

296 **4 Comparison of model and observations**

297 As in Grant et al. (2015), only observational data from near-neutral or transition-to-
298 stable conditions is used in order to allow comparison with the neutral flow model
299 simulations. Two flow regimes of north-easterly and south-westerly are presented
300 here. These are the same cases used in Grant et al. (2015), where a detailed obser-
301 vational analysis of these cases is given. There are some issues with interpreting cup
302 anemometer measurements, particularly in a canopy flow. Firstly, the cup anemome-
303 ters have a stall speed (notionally 0.7 ms^{-1} in this case) below which they will not
304 turn, and so under low wind conditions (typical in the canopy) they will tend to give
305 an underestimate of the wind speed compared to sonic anemometer measurements.
306 Secondly, at higher wind speeds, the cup will respond both to the mean wind, but
307 also to larger turbulent gusts, and will therefore tend to overestimate the wind speed
308 so the measured wind speed is effectively $\sqrt{U^2 + 2k}$

309 Figure 4 shows wind roses from the 12 AWS and 3 tower sites for both observa-
310 tional and model data. The observations are for cases where the wind is broadly north-
311 easterly with the wind direction at AWS ARP (a ridge top site outside the canopy)
312 being between 50° and 90° . This equates to about 15 hours of data. The model results
313 are for a geostrophic wind direction of 90° , which gives a 2m wind direction at AWS
314 ARP of about 80° . Figure 4(a) show wind roses of 15-minute averaged winds from

315 the 15 hours of observational data, while Fig. 4(b) shows the equivalent wind rose plot
316 from the model, with just a single wind value at each location. Note the model is for
317 a representative geostrophic wind speed of 10 m s^{-1} . This gives winds at the AWSs
318 which are similar in magnitude to the observations, but the values cannot be directly
319 compared. It is worth noting that the red bins are for mean winds which are close to or
320 below the stall speed of the cup anemometers on the AWS and so the precise values
321 should be treated with some caution. It is likely that these are under-representing the
322 true wind speed due to stalling.

323 It is however interesting to look at the wind directions and the variations in wind
324 speed across the hill for both the observations and model. In the easterly case there
325 is evidence of flow separation in the observations from a number of the AWS sites
326 (Fig. 4a), with sites within the canopy on the ridge and over the lee slope showing
327 strong deviations from the geostrophic wind. The flow is generally not reversed, but
328 there can be significant variability in wind direction. Outside the canopy there is less
329 variability in wind direction with winds predominantly remaining north-easterly. As
330 might be expected, wind speeds outside the canopy are also higher than those in the
331 canopy. The tower profiles (Fig. 4c) show little sign of separation, with tower T1 (on
332 the lee slope) still showing broadly north-easterly winds, except at the lowest level in
333 the canopy where there is some indication of more south-easterly winds. This appears
334 to be a marginal case of flow separation and highlights how three-dimensional flow
335 separation can be over real terrain, in contrast to previous idealised two-dimensional
336 studies. In this case the model predictions broadly agree with the observations. Out-
337 side the canopy the predicted flow is easterly / north-easterly and stronger than inside

338 the canopy (Fig. 4b). Over the upwind slope the flow remains north-easterly, while
339 near the ridge the wind is more along the ridge. The two AWS sites near the forest
340 edge on the lee slope (ARA and ARC) show light winds and complete flow reversal.
341 This is rather more dramatic than the observations, and may reflect the fact that unre-
342 solved small scale local features are important in determining wind direction in very
343 light winds and under an adverse pressure gradient. The observations are particularly
344 variable at these sites. The model tower profiles (Fig. 4d) also look very similar to
345 the observations, and even show the same tendency for the flow to become south-
346 easterly at the lowest level on tower T1. The model also shows a similar (though less
347 pronounced) tendency for the wind to turn clockwise at lower levels on tower T2,
348 which is not seen in the observations. This tower is close to the summit of the ridge
349 and so the precise wind direction is likely to be quite sensitive to the exact location of
350 the grid point. In both observations and model, the results at tower T3 on the upwind
351 slope show a north-easterly wind at all levels. Broadly there is agreement between
352 the model and observations in terms of the wind speeds. The highest winds are seen
353 above the canopy, particularly at the top of tower T2 near the ridge summit. The low-
354 est winds in the observations are at the lower levels on towers T1 and T2. The model
355 is slightly different, with low wind speeds low down on tower T1, but slightly higher
356 winds at the bottom of tower T2. Again the differences here perhaps represent the
357 sensitivity of the exact grid location at the ridge top.

358 Figure 5 is similar to Fig. 4, except that results are for broadly south-westerly
359 winds (observed wind directions in the range 240° to 260° - about 50 hours of data).
360 The model results are for a westerly geostrophic wind (corresponding to a wind di-

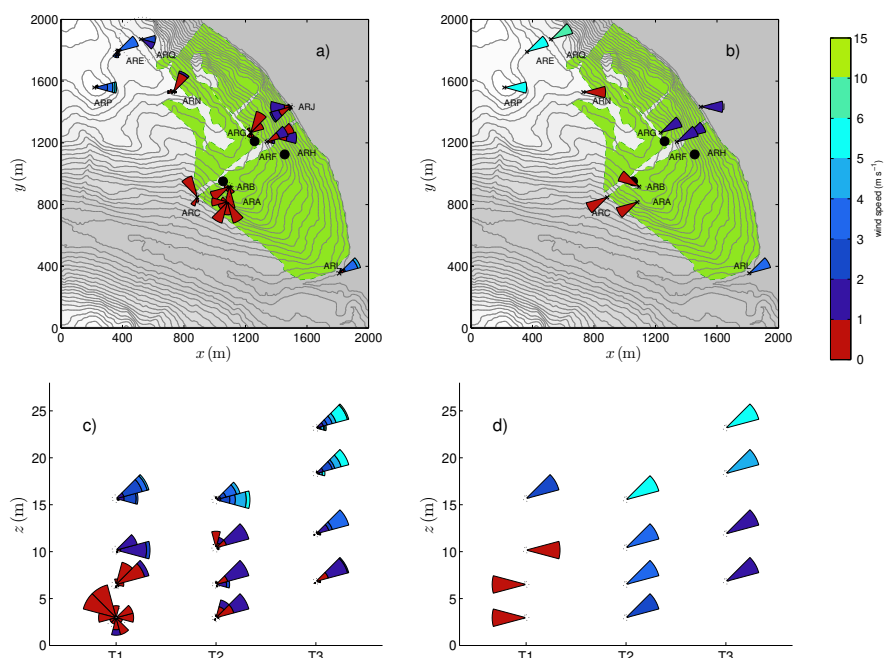


Fig. 4 Wind roses for the 12 AWS sites (a,b) marked with letters ARA to ARQ and 3 tower sites (T1, T2 and T3) (c,d). Results are from observations with north-easterly winds (a,c) and from the model simulation with a 10 m s^{-1} easterly geostrophic wind (b,d). The grey shading is height, with contours plotted every 10m. On the maps the locations of the three towers are marked with black circles.

361 rection of about 260° at 2m at AWS ARP). The ridge is asymmetric with the eastern
 362 slope steeper than the western slope and so for westerly winds the lee slope is steeper
 363 and flow separation occurs more easily than for easterly winds. The AWS observa-
 364 tions (Fig. 5a) show very weak winds and reversed flow at all the AWS sites near the
 365 ridge and over the lee slope (ARF, ARG, ARH, ARN). Even the AWS on the coast
 366 (ARJ) outside the forest shows reversed flow. The observations show large deviations
 367 in the flow near the upwind canopy edge as well (ARA, ARB, ARC), possible due to
 368 canopy edge effects or local features of the terrain or canopy. The tower observations

(Fig. 5c) corroborate this picture. Tower T3 over the lee slope shows reversed flow up to the top (about 23 m), which is well above canopy top. Tower T2 appears to be close to the separation point and the lowest two instrument heights show reversed flow, the flow is roughly southerly at the next height, and the flow is still westerly at the top of the tower. Again the model shows very similar behaviour to the observations (Fig. 5c), with the AWS sites over the lee slope demonstrating reversed flow. The directions are similar to those seen in the observations. The most noticeable difference is that the model shows more consistently westerly winds over the upwind slope compared to the observations (ARA, ARB, ARC). Since these sites also showed more variability in the observations in the easterly wind cases it seems likely that the deviations are due to unresolved local features of the terrain or forest canopy. The model profiles from the tower sites (Fig. 5d) show a remarkable similarity to the observations, capturing the flow reversal at tower T3 and the turning of the wind with height at tower T2. The magnitudes of the model winds also appear to vary between locations in a similar way to the observations. As a sensitivity test to the choice of geostrophic wind speed in the model an additional simulation for the south-westerly case was done with a higher geostrophic wind speed of 20 ms^{-1} . Results for the sensitivity test (not shown) were very similar to Fig. 5. Visually, there were only very minor differences in the normalised profiles, most noticeably at T2. This supports the comparison of the model with normalised observations over a range of background wind speeds. It also highlights the sensitivity of T2, which is perhaps not surprising given its proximity to the separation point.

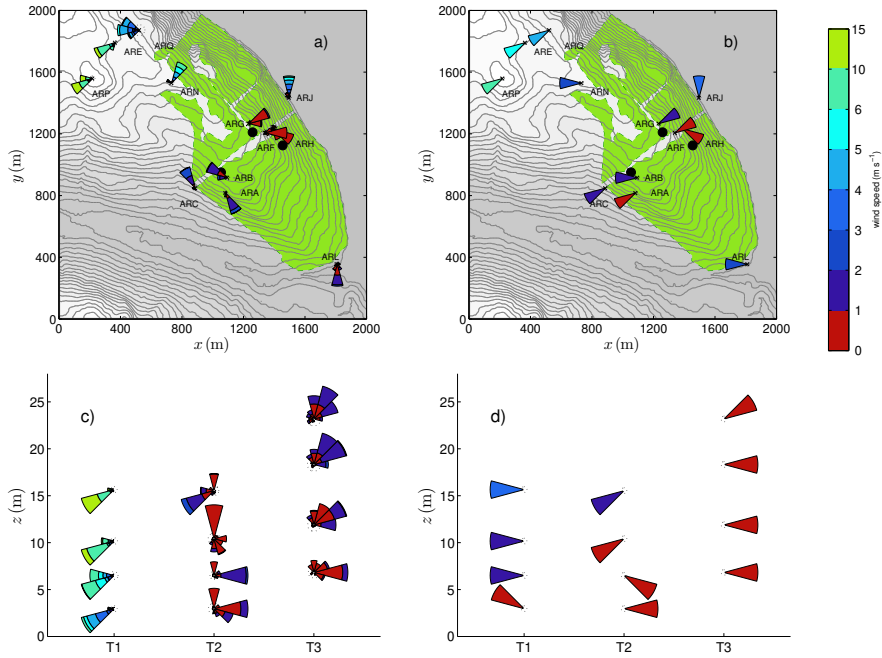


Fig. 5 Wind roses for the 12 AWS sites (a,b) marked with letters ARA to ARQ and 3 tower sites (T1, T2 and T3) (c,d). Results are from observations with south-westerly winds (a,c) and from the model simulation with a 10 m s^{-1} westerly geostrophic wind (b,d). The grey shading is height, with contours plotted every 10m. On the maps the locations of the three towers are marked with black circles.

391 Figures 6 and 7 provide a more detailed comparison of the mean wind profiles
 392 from the three towers, and also the profiles of momentum fluxes and turbulent ki-
 393 netic energy. To allow for a more quantitative comparison between observations and
 394 model the profiles are all normalised using a reference velocity U_{ref} which, for both
 395 the observations and the model, is taken as the wind speed at the height of the high-
 396 est instrument on the upwind tower (tower T1 for south-westerlies and tower T3 for
 397 north-easterlies). This normalisation is to account for differences in the background
 398 windspeed between the model and the different observations. Table 1 gives the value

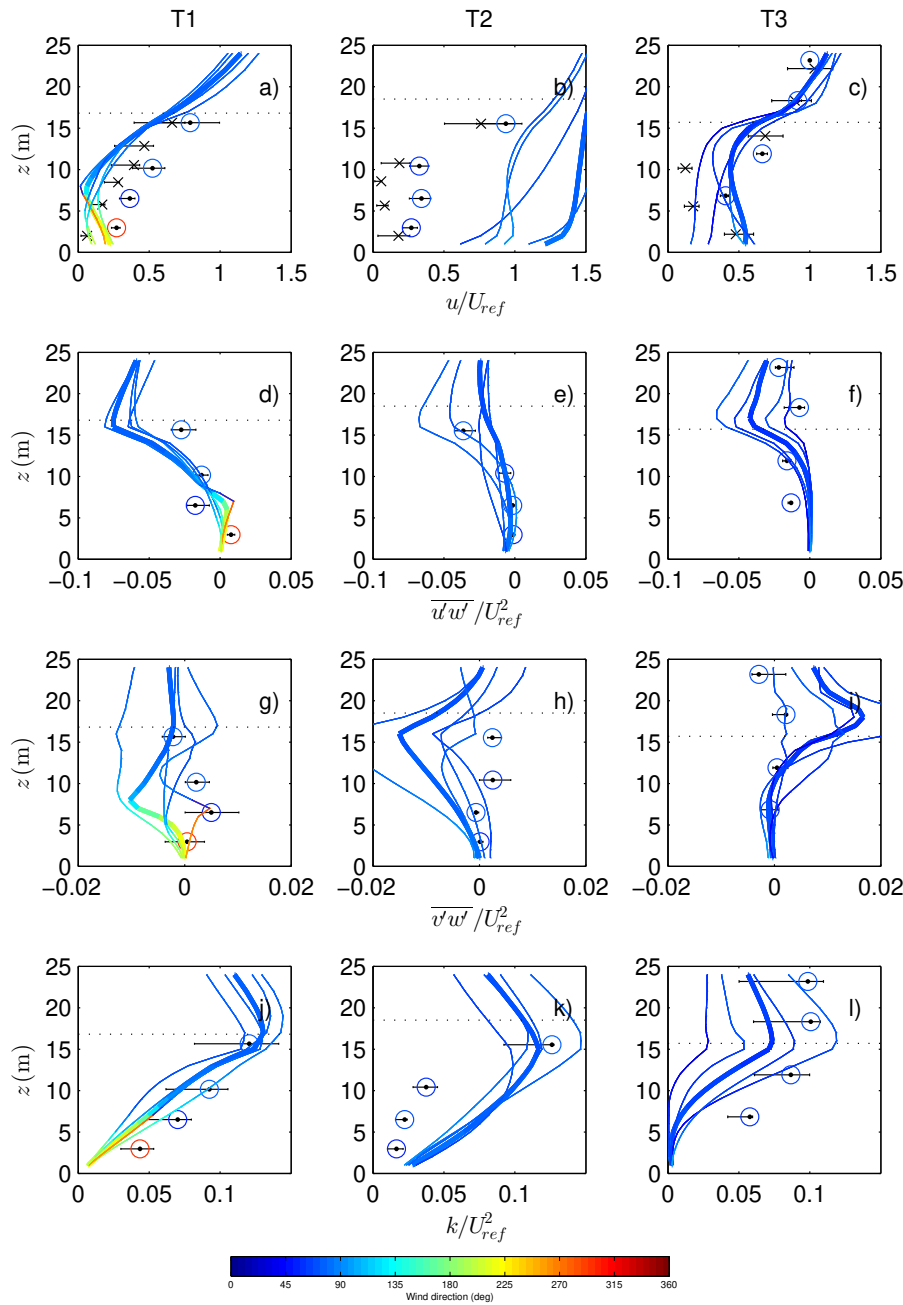


Fig. 6 Profiles for the north-easterly case of (a-c) wind speed, (d-f) streamwise momentum flux $\overline{u'w'}$, (g-i) cross-stream momentum flux $\overline{v'w'}$ and (j-l) turbulent kinetic energy, all normalised with a reference velocity U_{ref} taken at the height of the top instrument on the upstream tower T3. Symbols show the mean value from the observations and the error bar shows the interquartile range. The coloured circles represent measurements from the sonic anemometers, with the colour denoting the wind direction. The crosses are measurements from the cup anemometers on the towers. The solid lines show interpolated model profiles at the site of the tower (thick line) and at points 25m to the north, south, east and west of the tower (thin lines), again coloured according to wind direction. The horizontal dotted line marks the approximate canopy top at each tower.

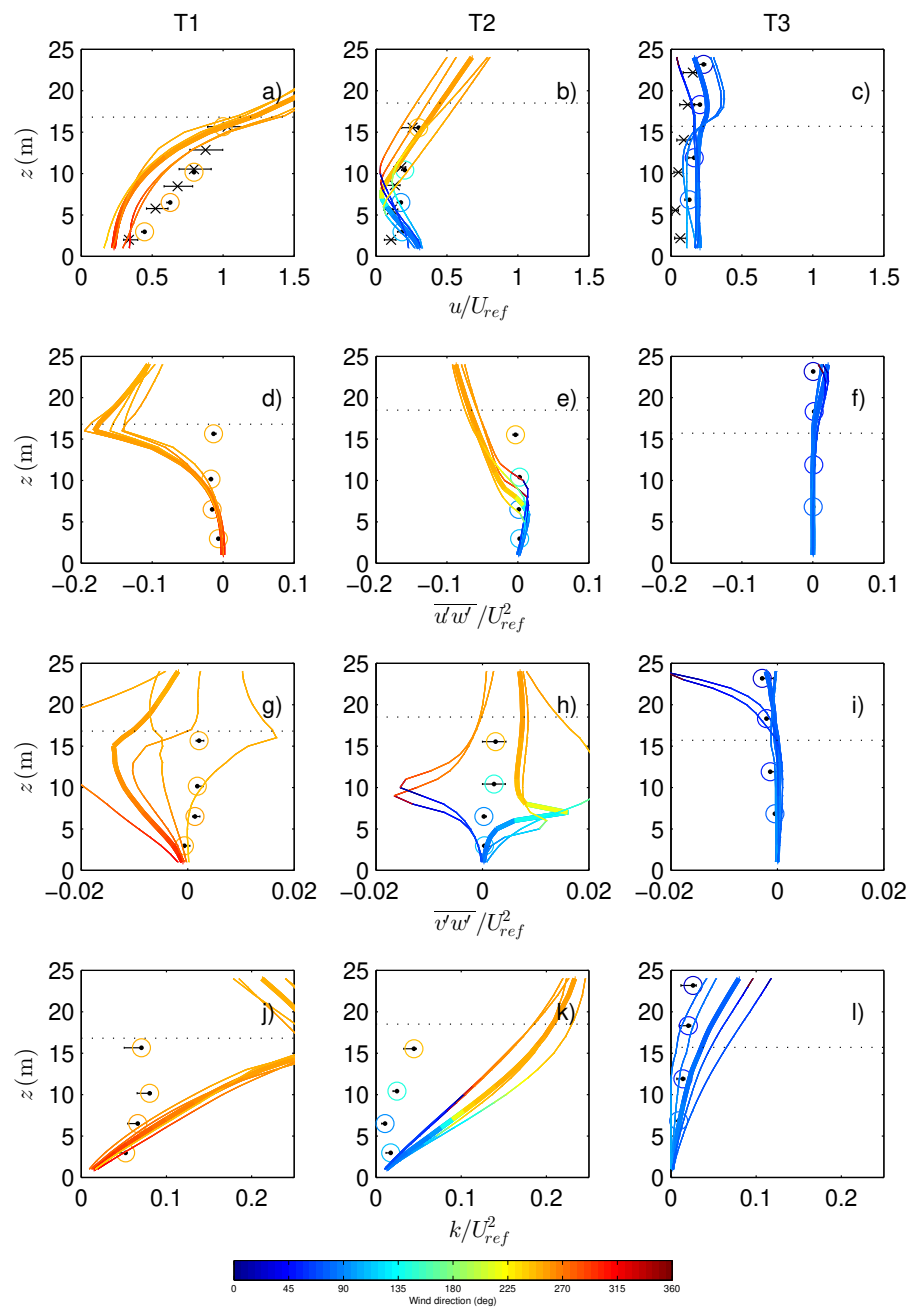


Fig. 7 As for Fig 6, but for the south-westerly case with U_{ref} taken as the top of tower T1.

Table 1 Values of the reference wind speed U_{ref} from the observations (median and interquartile range) and from the model for the north-easterly and south-westerly cases.

Wind direction	Reference tower	Median wind (m s^{-1})	Interquartile range (m s^{-1})	Model wind (m s^{-1})
NE	T3	4.3	2.8 – 5.9	5.4
SW	T1	10.0	7.9 – 12.5	3.7

399 for U_{ref} from the model and the median and interquartile range from the observations
400 for each wind direction. Several interpolated model profiles are shown, one from the
401 location of each tower and 4 more from 25 m north, south, east and west of the tower
402 (25 m is half the grid resolution of the model) to give an idea of the spatial variability
403 in the model, and hence the possible uncertainty in the model-observation compari-
404 son. It is worth noting that the mean wind speeds measured by the cup anemometers
405 are lower than those measured by the sonic anemometers as a result of stalling at low
406 wind speeds in the canopy. This problem is particularly noticeable in Fig 6(a)-(c) due
407 to the lower wind speeds in the north-easterly flow conditions.

408 For north-easterly cases (Fig 6) the model mean wind profiles at towers T1 and
409 T3 are in reasonable agreement with the observations, however the modelled pro-
410 files at tower T2 appear to significantly overpredict the wind speed, although they do
411 capture a profile with fairly constant wind speeds in the canopy and increasing wind
412 speeds above. There is also a large spread between the different model profiles sug-
413 gesting a region of complex canopy cover with large differences in wind speed over
414 short spatial distances. Bearing this in mind, along with the relatively simple treat-
415 ment of the canopy properties (uniform canopy height and density everywhere within

416 the canopy) it is perhaps not surprising that the model and observations show some
417 discrepancy. Tower T2 is characterised by quite different canopy cover to the east
418 (relatively sparse larch) and to the west (dense spruce), and there is a fire break to the
419 south, so the uniform canopy parameters are not necessarily a good approximation
420 at this location. Interestingly the profiles of streamwise momentum flux, $\overline{u'w'}$, are in
421 good agreement at all three towers. Note also that there is very little variability in the
422 normalised observations of streamwise momentum flux, suggesting that the single
423 reference velocity at the top of tower T3 provides a good scaling for the momentum
424 flux. The relative accuracy of the streamwise momentum flux predictions at T2 is
425 likely to be due to the fact the model captures the right wind shear profile through-
426 out most of the canopy, it's just that the wind speeds are consistently too large. In
427 contrast the profiles of $\overline{v'w'}$ show generally less good agreement between model and
428 observations. The model profiles do demonstrate a significant degree of variability
429 suggesting that $\overline{v'w'}$ is sensitive to the details of the local canopy and flow structure.
430 Comparisons of turbulent kinetic energy profiles between the model and observations
431 are also reasonable at T1 and T3, although at T2 the model appears to consistently
432 overpredict the turbulent kinetic energy within the canopy, which may be related to
433 the overprediction of the wind speeds in this case.

434 For south-westerly cases (Fig 7) the model mean wind profiles at T2 and T3 show
435 reasonable agreement with the observations, although the model seems to predict
436 more wind shear at T2 than is seen in the observations. At T1, the comparison is a
437 little less good, with the model underpredicting wind speeds below canopy top and
438 too strong a shear near canopy top. T1 is sat on a small outcrop, and in south-westerly

439 winds the flow is likely to accelerate over this outcrop, rather than passing through the
440 upwind canopy, but this feature is not well resolved by the model with the given 50m
441 horizontal resolution. Streamwise momentum fluxes are also in reasonable agreement
442 at most locations, except at the top of towers T1 and T2 where the model predicts a
443 much more rapid increase in the momentum flux than was observed. There is slightly
444 more wind shear in the model wind profiles, but not enough to account for the large
445 increase in momentum flux. The model profiles are very consistent and so this does
446 not appear to be due to spatial heterogeneity. It may be due to slight differences in
447 the canopy height between the model and observations, since the model assumes a
448 constant height of 15 m, or due to vertical variations in the canopy structure which are
449 not represented in the model simulation. Once again across-stream momentum fluxes
450 $\overline{v'w'}$ are very variable and show little agreement between model and observations
451 except at T3. This highlights the very three-dimensional nature of the flow at T1
452 and T2. For the south westerly cases turbulent kinetic energy profiles seem to be
453 overpredicted by the model at most heights, even where the momentum fluxes are in
454 reasonable agreement. This is most pronounced at T1 and T2. The overprediction of
455 shear near the canopy top may lead to extra generation of turbulent kinetic energy in
456 the model, which is then mixed down into the canopy. A further possibility is that
457 the simple representation of dissipation used in the model is not correct in complex
458 heterogeneous canopies. Further work is needed to understand these discrepancies.

459 Overall the model reproduces surprisingly well the observed patterns of wind
460 speed and direction over the hill. Those sites where the agreement is less good appear
461 to be primarily located close to the forest edge or near the ridge top at tower T2.

462 The model also appears to often capture the observed streamwise momentum fluxes,
463 although the across-stream momentum fluxes and turbulent kinetic energy profiles
464 are not always captured as accurately. The agreement gives confidence in using the
465 model results to study more closely the patterns of mean flow and flow separation
466 over the ridge.

467 **5 Flow separation and sensitivity to surface parametrization**

468 The results of Ross and Vosper (2005) suggested that flow separation is an intrinsic
469 feature of uniform canopy flows over idealised hills, and that this is fundamentally
470 different to flow separation over a hill with a rough surface. Here the sensitivity of the
471 model results to the surface parametrization over a more complex and realistic hill is
472 investigated, with particular focus on flow separation.

473 To test the importance of explicitly resolving the canopy in these simulations the
474 westerly wind case was re-run with the forest canopy being represented by a rough-
475 ness length parametrization rather than with the explicit canopy model. The rough-
476 ness length was chosen to match the equivalent roughness of the canopy, $z_0 = 0.35$
477 (see e.g. Ross and Vosper, 2005). All other aspects of the simulation were unchanged.
478 Figure 8 shows the wind roses from this simulation. In comparison with Fig. 5 there
479 is clearly less strong flow separation with the roughness length parametrization of the
480 surface. The sites that would be in the canopy over the lee slope show a flow which
481 is slowed and deflected along the slope to the south rather than being completely re-
482 versed as occurs with the canopy model. Outside the canopy there is little difference
483 between the results, suggesting that the impact of the canopy is relatively localised. In

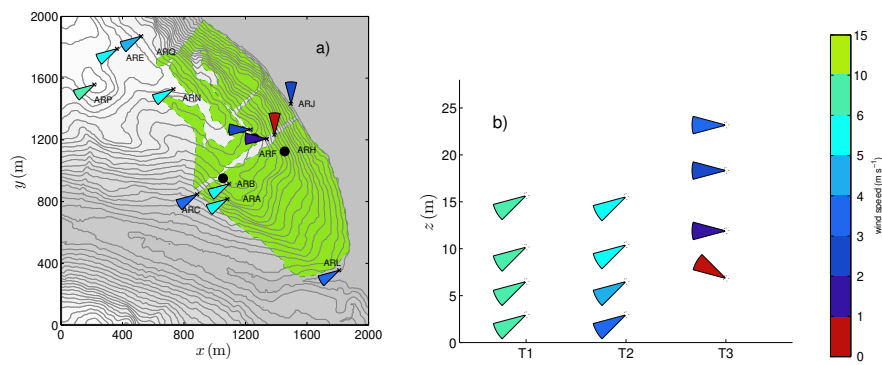


Fig. 8 Wind roses from the model simulation with westerly winds and a roughness length parametrization of the canopy. Results are shown at the 12 AWS sites (a) and the 3 towers (b).

484 the vertical (not shown) the region in which the flow is reversed or strongly deflected
 485 appears to extend up to about 55m above ground level (40m above the canopy top)
 486 with the explicit canopy model. In contrast, with the roughness length parametriza-
 487 tion the depth and horizontal extent of the region of strongly deflected flow is much
 488 reduced, reaching a maximum height of only about 12m above ground level. This
 489 suggests that even above the canopy, perhaps up to a couple of times the canopy
 490 height, the flow may be fundamentally different under conditions of flow separation
 491 depending on the way the effect of the canopy is modelled.

492 In three dimensions it is hard to identify flow separation in the velocity field. Un-
 493 like in two dimensions it is not simply a matter of looking for reversed flow since the
 494 flow may be deflected rather than reversed. This makes interpreting the flow pattern
 495 based on point observations tricky. Using the model allows a better understanding of
 496 the flow across the whole ridge, but it is still difficult to identify flow separation from
 497 near surface winds. As Hunt et al. (1978) showed, flow separation is associated with
 498 a singularity in the surface stress field and this can provide an alternative method for

499 identifying points or lines where the flow separates from or reattaches to the surface
 500 in three-dimensional flows. The surface stress is given by $\partial \mathbf{u}_s / \partial n$ where \mathbf{u}_s is the ve-
 501 locity tangential to the surface and n is the normal to the surface and so the surface
 502 stress gives an indication of the flow direction at the surface, but has the advantage
 503 of being non-zero, except where flow separates or reattaches. Wood (1995) suggested
 504 using plots of surface stress “streamlines” or streaks to identify these singularities.
 505 The streaks are plotted by calculating a series of two-dimensional surface trajectories
 506 (x,y) , where the two horizontal components of the surface stress take the role of the
 507 velocity field so

$$\frac{dx}{dt} = \tau_x \quad \frac{dy}{dt} = \tau_y. \quad (2)$$

508 The streaks are initialised from a series of points across the model domain and then
 509 calculated by integrating the trajectories forward and backwards for a specified length
 510 time. This works well for the examples used by Wood (1995), however the large
 511 difference between surface stress values inside and outside the canopy means that
 512 streaks in the canopy are very short. To circumvent this problem, we use a longer
 513 integration time, but limit the length of the streaks plotted so that streaks outside
 514 the canopy are not too long. The surface stresses are interpolated from the model
 515 grid using bilinear interpolation and the integration is carried out using the ode45
 516 function in Matlab. Using this approach and integrating forward numerically from
 517 $t = 0$ to $t = 20000$, and limiting the length of the streaks to 500m gives much more
 518 even lengths of streaks inside and outside the canopy, and makes visualisation of flow
 519 separation much easier in partially forested flows. Locations where the surface stress
 520 streaks all converge at a line or point are associated with flow separating from the

521 surface, while locations where the surface stress streaks all diverge from a line or
522 point are associated with flow reattaching to the surface.

523 Figure 9 shows plots of the surface stress streaks calculated from the model. For-
524 ward trajectories (blue) show flow separation and backward trajectories (red) show
525 reattachment. Wind direction vectors are also plotted at the points where trajectories
526 are initiated. For the easterly wind simulation (Fig. 9a) the surface stress plot clearly
527 illustrates the flow separation occurring over the lee slope on the forested part of the
528 ridge. There is one clear separation line just upwind of the ridge summit stretching
529 right along the forested part of the ridge there is also some indication of a second
530 separation line downwind of the ridge on the southern shoulder of the ridge. Reat-
531 tachment appears to occur at a singular point on the lee slope close to $x = 1300$ m
532 and $y = 1100$ m. This highlights the rather complicated three-dimensional structure
533 of the flow separation over a real ridge with heterogeneous canopy cover in compar-
534 ison with previous idealised two-dimensional modelling and laboratory studies. To
535 the north where there is no forest cover then the stress streaks pass right over the
536 ridge showing that flow separation does not occur, even though the ridge is slightly
537 higher at this point. Around the southern edge of the ridge, outside the canopy the
538 stress streaks run more or less parallel to the lower edge of the canopy and the con-
539 tours. This demonstrates the importance of flow around the southern end of the ridge
540 in easterly flow.

541 In contrast, for the westerly case (Fig. 9b) where the steep eastern slope of the
542 ridge is on the downwind side there is clear evidence of flow separation all along
543 the summit of the ridge, with reattachment occurring somewhere off the coast. Even

544 without the forest canopy this slope is steep enough to generate flow separation. In
545 this case there is a single separation line running right down the ridge. Outside the
546 canopy the separation line is downwind of the ridge summit, while within the canopy
547 separation occurs nearer the ridge summit. The flow off the coast remains almost
548 parallel to the ridge and to the coastline, suggesting that the region of separated flow
549 extends well beyond the foot of the ridge and is therefore much larger than in the
550 easterly wind case. The streaks in this case also suggest a rather less important role
551 for flow around the southern end of the ridge in westerly flow. These figures support
552 the interpretation of the flow separation based on the observed and model wind fields
553 made above and highlight the differences between cases with steep lee slopes where
554 flow separation would occur anyway (westerly flow) and less steep lee slopes, where
555 flow separation requires the presence of the canopy (easterly flow).

556 The conclusions on the sensitivity of the results to the explicit canopy parametriza-
557 tion are supported by the surface stress plot for the roughness length simulations. For
558 the easterly wind case (Fig. 9c) no flow separation was observed at all in the sur-
559 face stress streaks with a roughness length parametrization, in clear contrast to the
560 simulation with an explicit canopy. For the westerly case (Fig. 9d) a clear separa-
561 tion line downwind of the summit of the ridge is apparent with the roughness length
562 parametrization. Outside the canopy the streaks look very similar in the two sim-
563 ulations. Inside the canopy, parametrizing the canopy by a roughness length shifts
564 the flow separation further down the lee slope, and significantly reduces the variabil-
565 ity caused by the heterogeneous canopy cover and channelling through gaps in the
566 canopy. Explicitly modelling the canopy appears to be essential to capture the flow

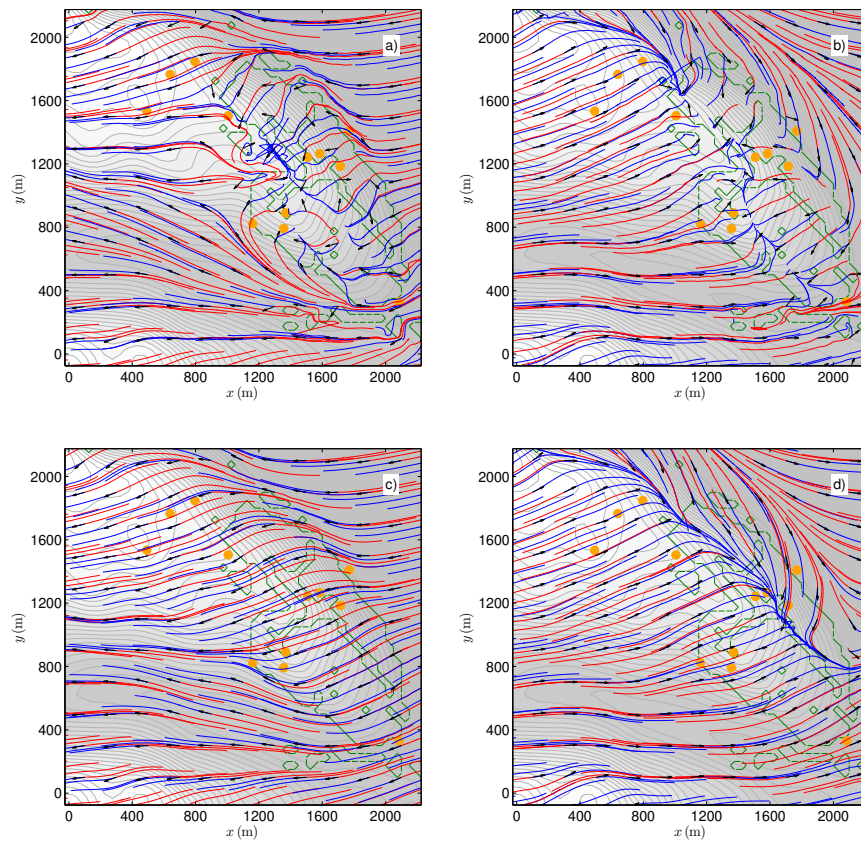


Fig. 9 Surface stress streaks from the model (forward trajectories - blue lines, backward trajectories - red lines) plotted over the height contours (at 10m intervals). Also plotted are wind direction arrows. Results are shown for easterly (a, c) and westerly (b, d) winds. Subfigures a), b) are with the explicit canopy model and c), d) are with a roughness length parametrization of the canopy. The orange dots show the sites of the AWS.

567 separation in the easterly case with a shallow lee slope, and even in the westerly case
 568 with a steeper lee slope the explicit canopy model significantly changes the location
 569 and magnitude of the separated region.

6 Discussion and conclusions

Flow over realistic complex terrain with variable forest cover, such as the Leac Gharbh ridge, is complicated and the local wind direction depends strongly on the local terrain and forest cover. Burns et al. (2011), one of the few other observational studies in complex terrain, draws similar conclusions. For flow which is close to neutral, high resolution numerical simulations with an explicit canopy model reproduce many of the features of the observed flow, however high quality input data sets for the terrain and the forest canopy are essential. High resolution terrain data sets are generally available, however details of forest canopy parameters are generally harder to obtain and require dedicated surveys. Available mapping products may provide details of the forest coverage, but they rarely contain details on the nature of the forest, the canopy height, or the canopy density. These details are essential for successful modelling of the flow in or near the canopy. Other recent studies (Burns et al., 2011; Desmond et al., 2014; Schlegel et al., 2015) have also highlighted the need for detailed canopy structure to accurately model heterogeneous canopy flows. Indeed in their study Desmond et al. (2014) saw more sensitivity to realistic canopy structure (particularly vertical structure) than they did to the turbulence closure model used. Recent progress using lidar offers exciting possibilities for detailed three-dimensional mapping of canopy structure (Boudreault et al., 2015), but unfortunately such a survey was not available at this site.

Near the edge of the forest canopy there appears to be greater discrepancy between the model and observations. This is partly due to the limitations of the forestry data, but more fundamentally may be linked to the horizontal resolution of the simu-

593 lations. At the edge of a uniform canopy the flow adjusts to the canopy over a distance
594 of order $6L_c$ where $L_c = 1/(C_d a)$ is the canopy adjustment length scale (Belcher et al.,
595 2012; Ross and Baker, 2013). For the canopy parameters here this gives $L_c = 4$ m and
596 so the flow adjusts over a distance of about 24 m, roughly half of the horizontal grid
597 spacing. Therefore the details of flow near the canopy edge will not be captured ac-
598 curately. Unfortunately this is often likely to be the case in real simulations where
599 the desired horizontal resolution has to be balanced with the overall computational
600 requirements of the simulation. The idealised simulations of Ross and Baker (2013)
601 suggest that at a distance greater than about $6L_c$ from the canopy edge the flow in the
602 canopy is dominated by the effect of the hill and not the canopy edge. This also seems
603 to be the case in these more realistic simulations with complex terrain and forest cover
604 since the agreement between observations and model at sites away from forest edges
605 is much better. A further complication is that adjustment can take much longer for
606 non-uniform canopies with a sparse sub-canopy trunk space (Dupont et al., 2011)
607 due to sub-canopy jets penetrating deep into the forest, although the dense canopy
608 cover over most of this field site makes this relatively unlikely.

609 The other significant discrepancy appears to be at tower T2, particularly in east-
610 erly wind cases. It may be that this site, near the ridge top and close to the line
611 of separation is particularly sensitive to small changes in the measurement position.
612 This location is also where the assumptions of a mixing length turbulence closure
613 seemed to be weakest, with a less clear relationship between the momentum flux
614 and the observed shear stress and with a strong directional shear. It is possible that
615 these factors are linked and that part of the reason for the slightly larger disagreement

616 between model and observations near the ridge top is the limitations of the model
617 turbulence closure scheme at this point. More work, possibly using computationally
618 expensive higher resolution simulations with the current turbulence closure scheme
619 or large-eddy simulations, is likely to be required to identify the real cause of this
620 discrepancy.

621 Although there is some debate in the literature about the suitability of mixing-
622 length closure schemes for canopy flows, these results suggest that such a model does
623 reproduce the main features of the mean flow seen in these observations over complex
624 terrain, at least in near-neutral flow. In part this may be due to the fact that advection
625 is important in the canopy and that this is driven by pressure gradients which are to
626 leading order a result of inviscid flow (see for example the analytical model of Finni-
627 gan and Belcher, 2004, for flow over a forested hill). Using the model results allows
628 a far more detailed understanding of the flow separation over such a complicated site
629 than is possible with the observations alone. The role of the canopy in promoting
630 flow separation over gentler slopes, and of shifting the location of flow separation
631 nearer the ridge over steeper slopes, seems clear and is in accord with theoretical
632 ideas developed by Finnigan and Belcher (2004) and Ross and Vosper (2005) over
633 idealised two-dimensional ridges. In contrast, simulations with a roughness length
634 parametrization fail to correctly predict the flow separation and pressure field over
635 the hill. While simulations such as this require a high vertical and horizontal resolu-
636 tion in order to correctly represent the canopy, the simplicity of the one-and-a-half
637 order closure scheme does mean that this approach is at least feasible for realistic
638 high resolution simulations of flow within and above forest canopies. In contrast,

639 more complicated approaches such as large-eddy simulations are at present usually
640 computationally unfeasible for modelling realistic flows with complex topography
641 and forest cover. Of course, for real applications stability effects are also important,
642 particularly in night time drainage flow conditions, and further work needs to be done
643 to see how well mixing-length schemes such as that used here can perform in these
644 cases.

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