# TURBULENT AIR FLOW IN FOREST STANDS: A WIND TUNNEL STUDY

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#### Abstract

This study used a wind tunnel to examine turbulent flow in thinned forests and downwind of shelterbelts. High frequency measurements of the wind components were made using a Dantec triaxial hot-wire probe. Four thinning treatments were studied, consisting of uniformly spaced model trees with plant area index (PAI) = 4.5, 1.7, 0.7 and 0.4. Turbulence statistics up to the fourth order, as well as results from quadrant analysis and spectral densities, were compared to a similar field study, showing good agreement between model and field results. Length and time scales associated with the canopy turbulence were described with linear stability theory. Forest thinning was shown to increase turbulent energy and momentum transport within the canopy. Four shelterbelt widths were studied in both laminar and turbulent flows. Profiles were measured at both upstream and downstream positions, and without shelterbelts present. Turbulence statistics up to the fourth order, spectral densities and results from quadrant analysis were examined. The turbulent flow cases showed little variation with width due to mixing of the flow by turbulence, while the laminar flow cases showed strong differences between widths extending much further downwind.

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# List of Symbols

a(z)	Foliage area density (m <sup>2</sup> m <sup>-3</sup> )
A(z)	Foliage area per unit tree height $(m^2 m^{-1})$
b	Tree breadth (m)
C <sub>d</sub>	Drag coefficient
d	Zero-plane displacement height (m)
D	Dissipation rate $(m^2 s^{-3})$
е	Turbulent kinetic energy $(m^2 s^{-2})$
$f_P$	Spectral peak from u spectra (Hz)
$f_{pw}$	Spectral peak from w spectra (Hz)
h	Tree height (m)
H	Hole size for quadrant analysis
H'	Hole size for 1/2 momentum transport
i	Variable used to indicate u, v, or w
<i>I<sub>i,H</sub></i>	Indicator function from quadrant analysis
Iu	Turbulent intensity
k	von Karman's constant (0.4)
K <sub>m</sub>	Momentum eddy diffusivity $(m^2 s^{-1})$
K <sub>m0</sub>	Neutral inertial sublayer eddy diffusivity for momentum $(m^2 s^{-1})$
k,	Resistance coefficient for shelterbelts
Kr <sub>i</sub>	Kurtosis of velocity, $i = u, v$ or $w$
L	Length scale above the roughness sublayer (m)

L <sub>s</sub> ,	Mixing layer length scale (m)
L <sub>u</sub>	Integral length scale (m)
Ps	Shear production of $e (m^2 s^{-3})$
$P_{w}$	Wake production of $e (m^2 s^{-3})$
Re	Reynolds number
r <sub>uw</sub>	Correlation coefficient
Sk <sub>i</sub>	Skewness of velocity, $i = u, v$ or $w$
Suu(f)	Spectral energy at frequency $f(m^2 s^{-1})$
Т	Averaging time interval (s)
$T_d$	Dispersive transport of $e (m^2 s^{-3})$
T <sub>m</sub>	Molecular transport of $e (m^2 s^{-3})$
$T_p$	Pressure transport of $e (m^2 s^{-3})$
$T_t$	Turbulent transport of $e (m^2 s^{-3})$
u', v', w'	Velocity fluctuations streamwise, cross-stream and vertical) (m $s^{-1}$ )
$\overline{u}, \overline{v}, \overline{w}$	Mean velocities (streamwise, cross-stream and vertical) (m $s^{-1}$ )
<i>u</i> +	Friction velocity (m $s^{-1}$ )
<i>u</i> <sub>1</sub> , <i>u</i> <sub>2</sub>	Velocities surrounding mixing layer (m s <sup>-1</sup> )
<i>u</i> <sub>c</sub>	Convective velocity of eddy structures (m $s^{-1}$ )
Ú <sub>h</sub>	Windspeed at $z = h \text{ (m s}^{-1})$
U	Velocity scale above the roughness sublayer (m $s^{-1}$ )
x, y, z	Co-ordinate axes (streamwise, cross-stream and vertical, respectively)
<i>z</i> <sub>0</sub>	Roughness length (m)

αμ	Kolmogorov constant
δ	Boundary layer depth (m)
Δ	Element separation (m)
3	Dissipation rate of $e (m^2 s^{-3})$
Φ	Pressure strain term from $\overline{u'w'}$ budget (m <sup>2</sup> s <sup>-3</sup> )
$\Lambda_x$	Wavelength of eddy structures (m)
ν	Kinematic viscosity $(m^2 s^{-1})$
$\sigma_{u}, \sigma_{v}, \sigma_{w}$	Standard deviations of $u$ , $v$ and $w$ (m s <sup>-1</sup> )
τ	Time lag (s)
$ au_0$	First zero crossing of auto-covariance function (s)

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## **1.Introduction**

Public demand for greater environmental awareness in the forest industry has spurred research into the impacts of various management practices. One important factor for the regeneration of stands and the health and growth of the remaining trees is microclimate. To fully predict the impact of forestry practices on microclimate, understanding turbulence in and around a forest is essential. This research was conducted in order to characterise the effects of several forestry practices on turbulence regimes. In particular, it examines thinning of forests, as happens with selective logging or shelterwoods, and shelterbelts, that are required by the Forest Practices Code of British Columbia in riparian zones.

Clearcutting has been the dominant method used to harvest timber in British Columbia. Alternative strategies include shelterwoods (where isolated trees or clumps of trees are left standing) and selective logging (where trees are harvested individually or in small groups). Two major concerns which must be addressed in selecting a harvest system are windthrow of remaining trees and microclimate for regeneration. Both are influenced strongly by windspeed and turbulence, which in turn are largely determined by clearing size, structure and orientation. The first part of this study intends to clarify the effects of uniform thinning on turbulence regimes within a forest. Uniform thinning resembles both single tree selection and shelterwoods, the former by direct analogy and the later because isolated trees or groups of trees spread over a clearing correspond to uniform thinning with very high percentage removal.

Shelterbelts appear in a variety of agricultural and forestry situations. In particular, riparian zones must be left uncut creating a narrow strip of vegetation, i.e. a shelterbelt. The width of these zones is regulated by the Forest Practices code; the second part of this study is concerned with how the width affects the wind forces acting on the trees and the downwind turbulence regime. These are important issues for the survival of the standing trees, which are usually in shallow, wet soils and prone to blowdown, and for the downwind microclimate, which will influence regeneration of the cut area.

Because of the extreme difficulties in making systematic, timely and cost-effective measurements in the field, this study was conducted in a wind tunnel. This has many advantages, allowing conditions to be carefully controlled and many measurements to be made in a short period of time. However, there is concern as to the applicability of wind tunnel results to real-world situations. This issue has been addressed as part of this study by comparing measurements made in the wind tunnel with published field data.

### 2. Turbulent Airflow in Canopies of Varying Density

### **2.1.Introduction**

Clearcutting has been the dominant method used to harvest timber in British Columbia. Current public demand for more aesthetic practises has driven the forest industry to consider alternative strategies, including shelterwoods (where isolated clumps of trees are left standing) and selective logging (where trees are harvested individually or in small groups). Two major concerns which must be addressed in selecting a harvest system are windthrow of remaining trees and microclimate for regeneration. Both are influenced strongly by windspeed and turbulence, which in turn are largely determined by clearing size, structure and orientation. This study was conducted to clarify the effects of uniform thinning on turbulence regimes within a forest. Uniform thinning resembles both single tree selection and shelterwoods, the former by direct analogy and the latter because isolated trees or groups of trees spread over a clearing correspond to uniform thinning with very high percentage removal. Because of the extreme difficulties in making systematic, timely and cost-effective measurements in the field, this study was conducted in a wind tunnel.

Recently Green *et al.* (1995) published a field study on the effects of tree spacing on turbulence characteristics. Their study was conducted in a Sitka spruce plantation in stands of three different densities. Amiro (1990) has also examined turbulence in three different boreal forests which had different densities due to different species composition in each stand. Lee and Black (1993) have reported on turbulence in a coastal Douglas-fir

stand in British Columbia. These studies have improved our understanding of turbulence and wind speed within and above forest canopies. The present work examines detailed measurements made under controlled conditions.

Wind tunnel studies have made significant contributions to understanding canopy flows, and to techniques for analysing turbulence data. Seginer *et al.* (1976) studied turbulence in and above a canopy composed of stiff cylindrical rods. Raupach *et al.* (1986) examined a canopy composed of metal strips. Brunet *et al.* (1994) explored turbulence in and above a canopy composed of thin flexible rods designed to simulate a wheat crop. These studies laid the foundation for understanding model canopies in the wind tunnel, and the range of canopy structures provides a framework for understanding the similarities and differences between our various thinning treatments.

The main objective of this chapter is to provide basic information on how turbulence statistics, length scales and spectra are affected by changes in canopy density. In order to accomplish this, high-frequency wind speed measurements have been made in and above four canopies with different planting densities. Results have been compared to the above-mentioned studies and discussed in terms of the real-world consequences of thinning to blow-down and forest microclimate. A second objective of this study was to examine the functioning of the wind tunnel model and the triaxial hot-wire probe in the high turbulent intensities of a canopy. A third objective was for this study to serve as a baseline reference for Chapter 3, which examines shelterbelts.

#### 2.2. Materials and Methods

## 2.2.1.Wind Tunnel

This experiment was carried out using the same wind tunnel and model as Chen et al. (1995 – hereafter referred to as CBNA) in their forest clearing experiment. The wind tunnel, owned by the Department of Mechanical Engineering at UBC, had a working section 25 m long by 2.4 m wide by 1.5 m high. A constant windspeed (as measured by a pitot tube-manometer system at the front of the tunnel) of 8 m s<sup>-1</sup> was used. Turbulent flow simulating the atmospheric boundary layer in neutral conditions was generated by Counihan spires (Counihan 1969), bluff bodies (boards), and roughness elements (wooden blocks) (Figure 2.1). Downstream of the blocks was 6 m of model forest extending across the tunnel. The equilibrated depth above the forest extended more than 2*h* (where *h* is tree height) above the tree tops (CBNA). The spires generate a boundary layer depth  $\delta$ approximately equal to their height, i.e.  $\delta = 1.25$  m. The origin of the wind-tunnel co-



Figure 2.1: Turbulence generating arrangement in the wind tunnel.

ordinate system used in this study was at the edge of the small blocks (x = 0 m), with z = 0at the floor and y = 0 halfway across the tunnel.

## 2.2.2.Instrumentation

Cartesian wind vectors were measured using a three-dimensional (3D) hot-film constant temperature anemometer (model 56C01, Dantec Electronik, Denmark). The probe (Model 55R91) had three orthogonal sensing fibres each at 54.7° to the probe axis, giving an acceptance cone of 70.6°. Calibration of the probe was performed following Jørgensen (1971), who described the effect of pitch and yaw on the signal from a single hot-wire. Full details of the calibration procedure are in Appendix I.

Voltage signals from the probe were recorded using a 486-based PC with an A/D board (Multi-functional carrier PCI-20098C-1, Intelligent Instrumentation, USA). At every sampling location signals from the 3 probe wires were recorded for 20 s at 500 Hz, creating raw voltage files of  $3 \times 10,000$  data points. Data was 'streamed' directly onto a hard disk drive and later transferred to optical disks. Processing of the data was done from the optical disks by first converting the raw voltage signals into velocity vectors in hot-wire co-ordinates, then performing a transformation to shift to wind-tunnel coordinates. Mean velocities ( $\overline{u}$ ,  $\overline{v}$  and  $\overline{w}$ ) and fluctuations (u', v' and w') were then calculated, where u, v and w are the streamwise, cross-stream and vertical components, respectively.

## **2.2.3.Model Trees and Forests**

The model forest consisted of individual model trees inserted into drilled holes in

sheets of  $1.2 \times 2.4$  m plywood. Full planting density was 500 trees m<sup>-2</sup> (used by CBNA) in staggered rows. The trees, composed of plastic strips with an interwound steel wire trunk, were 15 cm tall and 4.5 cm wide. They were made using materials supplied by a Christmas tree manufacturer (Barcana, Granby, Canada). Foliage was completely removed on the lowest 1.5 cm to simulate a branch-free 'trunk' space and the upper portion of the trees was trimmed to a conical shape, giving the per tree plant area profile shown in Figure 2.2.

The treatments used in this study consisted of four uniform thinnings (referred to as A, B, C and D) which maintained the relative positions of the trees while increasing the absolute spacings. Density, spacing and plant area index (PAI) are listed in Table 2.1 for



Figure 2.2: Average plant area per unit height for a single model tree.

Symbol	Source	Canopy	IAI	<i>h</i> (m)	<b>∆</b> (m)	и <sub>ћ</sub> (m s <sup>-1</sup> )	<i>u</i> • (m s <sup>-1</sup> )
			(m <sup>2</sup> m <sup>-2</sup> )				
A	present study	WT forest	4.5	0.15	0.01	1.97	0.66
B	-	÷	1.7	0.15	0.06	2.58	0.72
U	-	÷	0.7	0.15	0.11	2.97	0.71
D	Ŧ	£	0.4	0.15	0.16	3.46	0.70
GGH4	Green <i>et al.</i> (1995)	Spruce plantation	3.2	8	4	1	I
9HDD	Ŧ	z	1.5	7.5	9	ı	•
GGH8	Ŧ	<b>2</b>	0.8	7.6	8	•	I
AmiroA	Amiro (1990)	Boreal aspen	4	10	ı	ı	0.2 - 1.2
AmiroP	Ŧ	Boreal pine	Ю	15	I	ı	0.2 - 1.2
AmiroS	2	Boreal spruce	10	12	ı	ı	0.2 - 1.2
LB	Lee and Black (1993)	Dougls-fir	5.4	16.7	ı	1	~0.3
RCL	Raupach <i>et al.</i> (1986)	WT strips	0.23	0.06	0.074	3.40	1.03
BFR	Brunet <i>et al</i> . (1994)	WT wheat	0.47	0.05	0.005	2.88	0.87
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~	as follows: PAI - plant area index	$\kappa$ (m <sup>2</sup> m <sup>-2</sup> ), <i>h</i> - canopy height,	$\Delta$ - element s	pacing, u <sub>h</sub> - me	an wind speed	d at canopy top	<b>.</b>

Chapter 2: Forest Thinning

 $u \leftarrow friction velocity.$  WT = wind tunnel.

each treatment, along with other basic parameters. For comparison, parameters from other studies cited in this chapter are included in Table 2.1, along with the acronyms used to identify them in the text. It should be noted that GGH had a plant area distribution with the greatest density around z/h = 0.4 with much less leaf area in the upper third of the canopy. The two wind tunnel studies, RCL and BFR, had an even distribution with z, more like this study. Full density of 500 trees m<sup>-2</sup> was not used in this study due to the risk of damage to the probe within the canopy and expected probe inaccuracy for the very high turbulence intensities found in the full forest.

Four profiles were measured at each of four streamwise stations per treatment. For each treatment the same relative positions were used at each station (Figure 2.3). The stations, measured at position #1, were at x = 1.8, 4.3, 5.1 and 5.9 m. Little evolution was observed from 1.8 to 4.3 m, and none beyond that. Therefore, the profiles shown here are the even-weighted average of the twelve profiles with  $x \ge 4.3$  m. The exception to this was **A**, which was too dense to permit more than one profile at each station, therefore profiles



Figure 2.3: Profile positions relative to trees. Element separation,  $\Delta$ , also shown.

shown for A are averaged from three profiles at x = 3.1, 5.1 and 5.9 m. Weighting was not applied to any treatment because sample calculations showed no significant changes in first and second order statistics when a weighting scheme was tested. All profiles consisted of 30 vertical measurement points at z = 2, 3, 5, 7, ..., 59 cm (z/h = 0.13, 0.2, 0.33,0.47, ..., 3.93).

### 2.3.Results

#### 2.3.1.Mean Velocities

Profiles of mean horizontal wind speed normalised by friction velocity  $(\overline{u}/u_*)$  are shown in Figure 2.4. Since  $u_*$  was nearly constant across treatments, these profiles are a good indication of the shape of  $\overline{u}$  alone. As expected,  $\overline{u}$  increases in the canopy as it is thinned. This is also true above the canopy, extending above z/h = 2. Below z/h = 0.5 the profiles show relatively constant values, very much like a mixing layer. There is a clear inflection point for all treatments at z = h, and  $\partial \overline{u}/\partial z$  at z = h increases as PAI increases. All profiles show a suggestion of a secondary maximum near the floor. This is at the top of the defoliated trunk space, though CBNA have shown that this maximum is not caused by blow-through. A similar maximum has been reported by both LB and GGH in the field. Well above the canopy, treatment A departs significantly from the others. This is due to a higher free stream velocity (about 5% greater) and a lower  $u_*$ . Also shown in Figure 2.4 are 2 treatments from GGH with comparable PAI. Their profiles show the same features observed in this study and display similar magnitudes for



Figure 2.4: Mean horizontal windspeed (u) from four treatments normalised by friction velocity. Data from GGH also shown for comparison. Numbers in parentheses indicate PAI.

similar PAI. GGH observed lower values for similar PAI within the canopy, but this can be explained by the foliar distribution of their canopy, which had the greatest density concentrated around z/h = 0.4.

Figure 2.5 shows profiles of measured  $\overline{v}$  and  $\overline{w}$ . Conservation of mass implies that the large, relatively constant  $\overline{w}$  above the canopy is an error, since there is no horizontal acceleration within the canopy. These values could be interpreted as a probe misalignment of around  $-1.5^{\circ}$ . Another possibility is an unknown wind tunnel pattern, perhaps due to leakage. Currently there are measurements at only one cross-stream position; the possibility of a large scale circulation will have to be investigated in the future. Since these values are much smaller in laminar flow in the empty wind tunnel, it is possible that they are caused by turbulence.



Figure 2.5: Mean cross-stream (v) and vertical (w) velocities from the four treatments.

### **2.3.2.Roughness Parameters**

## 2.3.2.1. Momentum Transport and Friction Velocity

Profiles of normalised momentum transport  $(\overline{u'w'}/u_*^2)$ , shown in Figure 2.6, exhibit a clear constant stress layer above the canopy extending above z/h = 3. Within the canopy,  $\overline{u'w'}$  rapidly falls to zero, with the denser canopies producing a more rapid fall. Positive values of  $\overline{u'w'}$  are not seen in this study. GGH show similar results, with greater





PAI leading to a more rapid decline of  $\overline{u'w'}$  in the canopy. However, GGH show a less rapid fall for comparable PAI, due to their foliar distribution. Below z/h = 0.4, where most of their leaf area is located, their values agree closely with this study.

The measured  $\overline{u'w'}$  at the lowest point, z/h = 0.13, increased somewhat as the forest was thinned, however as a fraction of the constant stress layer, it increased from 2% in treatment A to only 7% in treatment D. This shows that little momentum is being absorbed by the floor, even when the canopy is very sparse. This is expected since the floor of the wind tunnel is very smooth.

Values for the friction velocity  $(u \cdot)$  (listed previously in Table 2.1) have been calculated as the average of  $(-\overline{u'w'})^{1/2}$  from z = h to 2h. For treatments **B**, **C** and **D** the values of  $u \cdot$  are within 3% of each other, while **A** is about 9% lower. For comparison Table 2.2 shows the predictions of Raupach's (1992) drag partition model (hereafter R92) for  $u \cdot u h$  together with values measured in this study. His predictions agree very well with the present observations, being within 10% for all treatments.

	Measured			Predicted		
Treatment	d/h	u√u <sub>k</sub>	z <sub>o</sub> /h	d/h	u√u <sub>k</sub>	z₀∕h
A	0.85	0.34	0.056	0.87	0.31	0.06
В	0.79	0.28	0.072	0.77	0.31	0.11
С	0.70	0.24	0.071	0.72	0.25	0.13
D	0.67	0.20	0.067	0.69	0.22	0.09

Table 2.2: Roughness parameters measured in the present study and predicted by R92.

#### 2.3.2.2.Zero-plane Displacement

Zero-plane displacement (d) was calculated as the height of mean momentum absorption (Jackson 1981), defined formally as:

$$d = \frac{\int_0^h z \frac{d\overline{u'w'}}{dz} dz}{\int_0^h \frac{d\overline{u'w'}}{dz} dz}.$$
 (2.1)

Numerical integration over the averaged profiles of  $\overline{u'w'}$  gave values for d/h listed in Table 2.2. Also listed are the predictions of R92, with measured and predicted values within 4% of each other for all treatments. A calculation of d with the drag coefficient ( $C_d$ ) assumed to be constant with height, i.e.

$$d = \left(\int_0^h z(\overline{u})^2 dz\right) / \left(\int_0^h (\overline{u})^2 dz\right), \qquad (2.2)$$

yielded values consistently about 10% lower than shown in Table 2.2.

#### 2.3.2.3.Roughness Length

Roughness length  $(z_0)$  was calculated using the logarithmic profile for the inertial sublayer in neutral conditions.

$$\overline{u}(z) = \frac{u_*}{k} \ln(\frac{z \cdot d}{z_0}), \qquad (2.3)$$

at z = 2h (with von Karman's constant k = 0.4). Values from this height were used because calculation of eddy diffusivities for momentum (discussed in section 2.3.4.2) showed a small neutral inertial sublayer around  $z/h \approx 2$  (Figure 2.14). This produced the values shown in Table 2.2. The agreement with R92 is not as good for  $z_0$ , though the trend of lower values for A and D agrees, showing that the maximum  $z_0$  occurs with PAI  $\approx 1$  to 2. It is possible that the measurements underestimate  $z_0$  because of the lack of a fully developed inertial sublayer. This happens in wind tunnels because the ceiling is on the order of 10*h*, as opposed to the planetary boundary layer which is on order of 100*h* for forest canopies.

#### **2.3.3.Turbulence Statistics**

#### 2.3.3.1.Standard Deviations

Figure 2.7 shows profiles of normalised standard deviations for the three wind components ( $\sigma_u/u$ ,  $\sigma_v/u$ , and  $\sigma_w/u$ ). Within the canopy these increase as density decreases. At z > h all three components rapidly fall to constant values which are not influ-



Figure 2.7: Mean profiles of normalised standard deviations of three wind components  $(\sigma_u/u_*, \sigma_v/u_* \text{ and } \sigma_w/u_*)$ . Values from GGH also shown. Legend in (b) applies to all plots, numbers in parentheses indicate PAI.

A (4.5)
B (1.7)
C (0.7)
D (0.4)
GGH4 (3.2)
GGH8 (0.8)

enced by density. Kaimal and Finnigan (1994) give typical roughness sublayer values for  $\sigma_u/u$  and  $\sigma_u/u$  of 2 and 1.1, respectively. Values for  $\sigma_u/u$  agree closely, though  $\sigma_u/u$  here is somewhat higher at 1.4. Values from GGH4 and GGH8 are also plotted in Figure 2.7. Again, these show excellent agreement, with GGH8 (PAI = 0.8) falling close to treatment C (PAI = 0.7), and GGH4 (PAI = 3.2) case falling in between treatments A and B (PAI = 4.5 and 1.7, respectively). GGH6, not shown, generally falls in between GGH4 and GGH8.

In contrast to  $\sigma_i/u_i$ , turbulence intensity  $(I_u = \sigma_u/\overline{u})$ , not shown here, increases as the density increases. Peak values of  $I_u$ , found at z/h = 0.5, increase from around 0.4 in **D** to 0.7 in **A**. Turbulent kinetic energy  $(e = \frac{1}{2}(\sigma_i^2))$ , however, naturally follows the plots in Figure 2.7 with a constant value above all the canopies of about 2 m<sup>2</sup> s<sup>-2</sup>.

### 2.3.3.2.Correlation Coefficient

Profiles of the correlation coefficient  $(r_{uw} = \overline{u'w'}/\sigma_u \sigma_w)$  are shown in Figure 2.8. There is a clear peak at z/h = 1, with the denser canopies being more negatively correlated. Above the canopy all four treatments rapidly collapse to  $r_{uw} = -0.35$  to -0.4, very close to typical atmospheric surface layer values. BFR found similar profiles of  $r_{uw}$  in their wind tunnel model of waving wheat (PAI = 0.47), suggesting that  $r_{uw}$  is not strongly affected by canopy structure and stiffness.



Figure 2.8: Profiles of correlation coefficient  $(r_{rre})$ .

### 2.3.3.3.Skewness and Kurtosis

Profiles of skewness  $(Sk_i = i^{\sqrt{3}}/\sigma_i^3, i = u, v \text{ or } w)$  are shown in Figure 2.9. All treatments collapse together rapidly above the canopy, while in the canopy skewness increases in magnitude with increasing density. Values from GGH4 and GGH8 are also shown, with excellent agreement for  $Sk_u$  and  $Sk_v$ , and good general agreement for  $Sk_w$ . GGH report higher values for  $Sk_w$  within the canopy, possibly due to our probe underestimating some w'events. This could happen when eddies outside the cone of acceptance of the probe are reported as being within the cone, thereby reducing the reported w and leading to an underestimation of  $Sk_w$ . This phenomenon was discovered during calibration of the probe and is caused by flow interference from the arms that hold the wires. On the

other hand, the difference could be due to the different PAI distributions. LB report  $Sk_u = 0.7$  and  $Sk_w = -0.5$  at z/h = 0.5 for their canopy of PAI = 5.4. Amiro (1990) also reports  $Sk_u = 1$  to 1.5 and  $Sk_w = -0.5$  to -1.2 for PAI = 2 to 10.



Profiles of kurtosis ( $Kr_i = \overline{i'^4}/\sigma_i^4$ , i = u, v or w) are shown in Figure 2.10. All treatments collapse together to the Gaussian value of 3 above the canopy, while at z < h  $Kr_i$  increases with increasing density.  $Kr_u$  was found to be greater than  $Kr_w$ , which is opposite of what GGH report. As with  $Sk_w$ , the probe may have underestimated  $Kr_w$ . LB and Amiro both report lower  $Kr_i$  values than this study for comparable PAI, and they report  $Kr_u$  higher than  $Kr_w$ . The differences between treatments in this study are larger and

more defined than seen by other researchers, which may be due to the PAI in this study being nearly uniform with z.



Figure 2.10: Kurtosis of the velocity components  $(Kr_{s'}, Kr_{v} \text{ and } Kr_{w})$ , shown with results from GGH.

	A (4.5)
	B (1.7)
<u> </u>	C (0.7)
•••••	D (0.4)
х	GGH4 (3.2)
+	GGH8 (0.8)

## 2.3.3.4.Integral Length Scale

The single-point Eulerian length scale as estimated from the integral time scale by applying Taylor's frozen-turbulence hypothesis is:

$$L_{i} = \frac{\left\langle \bar{i} \right\rangle}{\sigma_{i}^{2}} \int_{0}^{\tau_{0}} \overline{i'(t)i'(t+\tau)} d\tau \qquad (2.4)$$

where i = u or w,  $\tau$  is time lag and  $\tau_0$  is the first zero-crossing of the autocovariance function. Though this scale should only apply to cases of isotropic, stationary, homogenous turbulence, it is found to provide useful information when not all of these conditions are met. Profiles of the normalised length scales  $L_u/h$  and  $L_w/h$  are shown in Figure 2.11. Within the canopy all treatments show  $L_u/h < 1$ , while above z/h = 2 all treatments collapse together to  $L_u/h \approx 2.5$ . Values from GGH are also plotted, showing consistently greater values for both  $L_u/h$  and  $L_w/h$ . It is possible that they report higher values either



Figure 2.11: Profiles of horizontal and vertical integral length scales normalised by tree height (L/h). Data from GGH also shown, numbers in legend indicate PAI.

	A (4.5)
	B (1.7)
<u> </u>	C (0.7)
•••••	D (0.4)
x	GGH4 (3.2)
+	GGH8 (0.8)
0	RCL (0.23)
because of a different row configuration (their rows were not staggered) or because of the different PAI distribution in their study. Also shown are values from the metal strip canopy of RCL. Their values are similar to this study, given their PAI = 0.23.



To consider the effect of tree spacing on  $L_u$  and  $L_w$ , Figure 2.12 shows profiles of  $L_u/\Delta$  and  $L_w/\Delta$ , where  $\Delta$  is element spacing defined as the distance from one element to its closest downstream neighbour (see Figure 2.3). Again, values from GGH and RCL are also plotted. They collapse together very well, with  $L_u/\Delta$  falling to 1 in the canopy and

 $L_w/\Delta$  around 0.25 in the canopy. This suggests some control of in-canopy eddy size by element spacing. Above the canopy, however, the various treatments diverge considerably. The ratio  $h/\Delta$  ranges from 0.8 to 15 in the data shown, however the data of BFR (not shown here) does not show the collapse of  $L_r/\Delta$ , possibly because of the waving of their canopy and its very narrow spacing.

### 2.3.4.Drag Coefficient and Eddy Diffusivity

### 2.3.4.1.Drag Coefficient

 $C_d$  was calculated as a function of z for each treatment as

$$C_d = \frac{-2}{a(z)(\bar{u})^2} \frac{\partial \bar{u'w'}}{\partial z}.$$
 (2.5)

where the gradients were calculated by finite differences using the averaged profiles in Figure 2.6 yielding the profiles in Figure 2.13. These profiles show that  $C_d$  is not constant with height, invalidating equation (2.2). Overall,  $C_d$  decreases as PAI increases. Assuming the trees behave like cylinders of breadth, b = 4.5 cm, the Reynolds numbers ( $Re = \frac{1}{u} b/v$ ) for the treatments range from 1500 to 7000 for A to D, respectively. In this range, a cylinder has  $C_d = 1.0$ , while the canopies show  $C_d = 0.3$  to 0.4. Since  $C_d > 1$  would be expected if Re has been overestimated (which may be due to the small branches reducing the effective b) these results indicate a shelter effect which increases, though not at all z, as more trees are added to the canopy.





## 2.3.4.2.Eddy Diffusivity

Eddy diffusivities for momentum were calculated as

$$K_m = -\frac{\overline{u'w'}}{\partial \overline{u}/\partial \overline{z}}.$$
 (2.6)

Profiles of  $K_m$  are shown in Figure 2.14, along with the neutral stability inertial sublayer prediction  $K_{m0} = ku \cdot (z - d)$ . As found in previous wind-tunnel studies (BFR, RCL), the measured  $K_m$  is higher within the canopy and roughness sublayer due to wake effect turbulence and close to the neutral value around z/h = 2. Above that, the predicted values continue to rise while the measured values tend to stay at a constant value. Also seen in other wind tunnel studies (RCL, BFR), this indicates that the roughness sublayer blends directly into the outer layer with virtually no inertial sublayer, as discussed previously in Section 2.3.2.3.



Figure 2.14: Momentum eddy diffusivity  $(K_m)$  for the four treatments. Dotted line represents inertial-sublayer diffusivity  $K_{m0} = ku_n(z - d)$ .

## 2.3.5.Spectra

Normalised power spectra  $(f S_{uu}(f)/\sigma_u^2)$  of the *u* component are shown at four heights for all treatments in Figure 2.15. The spectra were computed based on Welch's method with an FFT using a Hanning window (Matlab Signal Processing Toolbox, Mathworks, Inc.). This method smoothes the high frequency signal at the expense of some of



Figure 2.15: Normalised power spectra of u for the four treatments at z/h = 0.73, 1.0, 1.67 and 3.93. Straight line shows -2/3 slope.



the low frequency signal. These spectra are from the profiles measured at x = 5.1 m (position #1). The spectra collapse together with this scaling, particularly in the low frequency end near the peak. At higher frequencies there is more scatter, with A having more energy. This is noticeable even at z/h = 3.93, where the canopy is not expected to influence high frequency motions. All spectra in Figure 2.15 show a clear inertial subrange following the -2/3 power law for about a decade. At the high frequencies the spectra show an increase in energy, most likely due to aliasing.

The spectral peak  $(f_p)$  was estimated for each measurement point with a separate calculation which computed the spectral density at many frequencies around the peak, enabling a more precise estimate. At  $z \ge h$ ,  $f_p = 3$  Hz for all treatments, while within the canopy  $f_p$  increased slightly. The constant  $f_p$  with height is consistent with coherent eddies of height  $\approx h$  for z/h < 2. Above this, the constant  $f_p$  suggests that the eddies scale to a velocity and length scale, U and L, with a ratio of order  $h/u_h$  (BFR, RCL). Following BFR and taking  $U \approx 6.5$  m s<sup>-1</sup> (an average speed above the canopy) gives  $L \approx 0.26\delta$  and peak wavelength  $U/f_p \approx 1.6\delta$ , comparable to their  $L = 0.21\delta$  and  $U/f_p = 1.7\delta$ . Note that  $L \approx L_u$  at z/h > 2.

Figure 2.16 shows  $f S_{ww}(f)/\sigma_w^2$  for the same measurement positions as Figure 2.15. The treatments collapse together at all frequencies with the scaling shown here. For these spectra  $f_{pw} \approx 2f_p$ . There is no clear inertial range present, instead there is a plateau at  $f > f_{pw}$ , which begins to fall slightly around f = 100 Hz. Broad peaks in  $f S_{ww}(f)$  have been reported before (RCL) but there is no obvious explanation for the lack of inertial subrange here unless it is due to the acceptance angle problem discussed in section 2.3.3.

Figure 2.17 shows the co-spectra for u'w'. These spectra do not collapse as well as the single-component spectra, with A having much less low frequency energy within and just above the canopy, indicating that little transport occurs through motions at these frequencies. These plots closely resemble the w spectra, with the peak between 5 and 10 Hz and a broad plateau at higher frequencies, indicating that w' is responsible for much of the momentum transport and that the transport happens across a range of higher frequencies. It is undoubtedly the influence of w on these co-spectra which prevents them from



Figure 2.16: Normalised power spectra of w for the four treatments at z/h = 0.73, 1.0, 1.67 and 3.93. Straight line shows -2/3 slope.

		A B C	
		D	
L	•		

showing the expected -4/3 slope inertial subrange.



Figure 2.17: Normalised power spectra of u'w' for the forthe treatments at z/h = 0.73, 1.0, 1.67 and 3.93.



### 2.3.6. Comparison with Linear Stability Theory

Linear stability theory considers oscillatory perturbations of a laminar flow and predicts the length and time scales of periodic modes that eventually develop into large scale coherent structures. Raupach *et al.* (1989) (hereafter RFB) have discussed the theory as it applies to canopy flows by examining the stability characteristics of plane inviscid shear flow with an inflection point. The theory considers the mixing region between two constant flows,  $u_1$  and  $u_2$ , and defines a length scale,  $L_s$ , which is equal to half the distance of the mixing layer. For the canopy case, the mixing layer extends from  $z = h - L_s$  to  $h + L_s$ . In the special case of  $u_1 = 0$  (with  $u_1$  being the canopy flow),  $L_s \approx u_h / (\partial u / \partial z)|_h$ .

The theory predicts that the wavelength,  $\Lambda_x$ , which is the streamwise distance between coherent eddies, is given by

$$\Lambda_x = \frac{2\pi}{0.4} L_s. \tag{2.7}$$

RFB suggest that  $\Lambda_x$  can also be estimated from the spectral peak  $(f_p)$  as

$$\Lambda_x = \frac{u_c}{f_p} \tag{2.8}$$

where  $u_c$  is the convective velocity of the coherent eddies. RFB say that  $u_h$  is a good estimator of  $u_c$  but Shaw *et al.* (1995) have recently presented measurements of  $u_c$  which show  $u_c \approx 2u_h$  in the canopy and roughness sublayer. Combining equations (2.7) and (2.8) yields an expression for  $u_c$ , i.e.

$$u_c = \frac{2\pi}{0.4} f_p L_s \,. \tag{2.9}$$

Visual inspection of the  $\overline{u}$  profiles in Figure 2.4 shows that  $L_s \approx h/2 = 0.075$  m for all treatments. For comparison, Table 2.3 lists values of  $L_s = u_h / (\partial u / \partial z)|_h$ . For A and B the agreement is close, since the assumption of  $\overline{u} = 0$  is a good approximation in the denser canopies. However, as the canopy is thinned,  $\overline{u}$  increases in the canopy and  $L_s$  can no longer be estimated in this way. For further calculations,  $L_s = 0.075$  m will be used for all treatments. From equation (2.7), this gives  $\Lambda_x = 1.2$  m for all treatments and, assuming that equation (2.8) holds for this data, equation (2.9) gives  $u_c = 3.5$  m s<sup>-1</sup>. Values of  $u_c/u_h$  listed in Table 2.3 show that  $u_c \approx 2u_h$  holds for the denser canopies, but as the canopy is

Treatment	$L_s = \frac{u_k}{\partial u/\partial z_k}$ (m)	$\frac{u_c}{u_h} = \frac{2\pi}{0.4} f_p \frac{h}{2}$
Α	0.06	1.8
В	0.09	1.4
С	0.11	1.2
D	0.16	1.0

thinned,  $u_h$  increases to approximately  $u_c$  in **D**.

Table 2.3: Values from linear stability computationsfor the four treatments.

### **2.3.7.Turbulence Budgets**

### 2.3.7.1.Turbulent Kinetic Energy

The TKE budget for stationary flow through a canopy with no streamwise evolution or buoyancy (after Raupach and Shaw, 1982) is

$$\frac{\partial \langle e \rangle}{\partial t} = -\langle \overline{u'w'} \rangle \frac{\partial \langle \overline{u} \rangle}{\partial z} - \langle \overline{u'_{i}u'_{j}}'' \frac{\partial \overline{u'_{i}}''}{\partial x_{j}} \rangle - \frac{\partial}{\partial z} \langle \overline{w'e} \rangle$$

$$P_{s} \qquad P_{w} \qquad T_{t}$$

$$-\frac{\partial}{\partial z} \langle \overline{w'e''} \rangle - \frac{\partial}{\partial z} \langle \overline{p'w'} \rangle + v \frac{\partial^{2}}{\partial z^{2}} \langle e \rangle - \langle e \rangle \qquad (2.10)$$

$$T_{d} \qquad T_{p} \qquad T_{m} \qquad D$$

where  $P_s$  is shear production,  $P_w$  is wake production,  $T_t$  is turbulent transport,  $T_d$  is dispersive transport,  $T_p$  is pressure redistribution,  $T_m$  is molecular transport, and  $D = -\varepsilon$  is the viscous dissipation. Brackets and double-primes represent volume average and fluctuations, respectively.  $P_s$  and  $T_t$  can be directly evaluated from our measurements and D has been estimated from the inertial subrange of the u spectra according to the Kolmogorov hypothesis:

$$fS_{uu}(f) = \alpha_{u} \varepsilon^{2/3} (2\pi f / \bar{u})^{-2/3} . \qquad (2.11)$$

with  $\alpha_u$  taken to be 0.55 (after BFR).  $T_d$  and  $T_m$  are thought to be negligible and  $P_w$  can be estimated (Raupach and Shaw 1982) as

$$P_{w} = -\left\langle \overline{u} \right\rangle \frac{\partial \left\langle \overline{u'w'} \right\rangle}{\partial z}.$$
 (2.12)

The residual is then thought to be approximately equal to  $T_{p}$ .

Profiles of the observed TKE budget are shown in Figure 2.18, normalised by  $h/u^{3}$ .  $P_s$ ,  $P_w$  and D all peak around z = h while D and  $T_t$  balance  $P_s$  above the canopy with little residual.  $T_t$  is a sink above the canopy and a source within the canopy. D is a greater loss term than  $T_t$  at all z. The residual is a large term in the canopy. Since it is expected to be composed mostly of  $T_p$  and to be on the same order as  $T_t$ , this could indicate an underestimate of D, possibly from 'leaf' scale motions, which are smaller than the space occupied by the three hot-wires and therefore unresolvable by them. If D has been underestimated in the canopy by a factor of 2, the residual would approximately equal  $-T_t$  everywhere but the region near the top of the canopy. This would bring the e budget from **D** (PAI = 0.4) into close agreement with the budget of BFR (PAI = 0.47).



 $P_s$  increases in the region of z = h with PAI. The peak of  $P_w$  is nearly constant across treatments, however it is more extensive inside the thinner canopies, occurring deeper within the canopy. Because of this, the ratio  $P_s/P_w$  is reduced as the canopy is thinned. As a sink,  $T_t$  shows little variation with density above the canopy, but inside the canopy it is a source term which is stronger for the denser canopies above z/h = 0.5, and stronger for the thinner canopies below that. Above and at the top of the canopy, D is a

larger sink as the density increases, while below z/h = 0.8 it becomes weaker as the PAI increases. The residual peak is therefore greatest and sharpest for the denser canopies. It should be noted that for A, all terms in the budget are essentially zero below z/h = 0.5.

### 2.3.7.2.Shear stress

With the same conditions as for the e budget (stationary flow with no evolution or buoyancy), the shear stress budget can be written as (BFR 1994)

$$\frac{\partial \langle \overline{u'w'} \rangle}{\partial t} = 0 = -\langle \overline{w'^2} \rangle \frac{\partial \langle \overline{u} \rangle}{\partial t} - \langle \overline{u'_1u'_j}, \frac{\partial \overline{u'_3}}{\partial t_j} + \overline{u'_3u'_j}, \frac{\partial \overline{u'_1}}{\partial t_j} \rangle - \frac{\partial}{\partial t} \langle \overline{u'w'^2} \rangle - P_s \qquad P_w \qquad T_t \\
- \frac{\partial}{\partial t} \langle \overline{w''u'w''} \rangle - \frac{\partial}{\partial t} \langle \overline{p'u'} \rangle + \langle \overline{p'(\frac{\partial u'}{\partial t} + \frac{\partial w'}{\partial t})} \rangle - 2\nu \langle \frac{\partial u'_1}{\partial t_j} \frac{\partial u'_3}{\partial t_j} \rangle + \\
T_d \qquad T_p \qquad \Phi \qquad D \\
+ \frac{1}{V} \iint_S \left[ \overline{v'_1(p'n_3 - \nu \frac{\partial u'_3}{\partial t})} + \overline{v'_3(p'n_1 - \nu \frac{\partial u'_1}{\partial t})} \right] dS \qquad (2.13) \\
P_v$$

where the terms have the same meaning as for the *TKE* budget with the addition of  $\Phi$ , which is pressure-strain term and the dominant force for dissipation, since D is generally negligible. Following RCL, we neglect  $T_d$ ,  $P_w$  and  $P_v$  while  $P_s$  and  $T_t$  can be evaluated directly from our measurements, leaving the residual equal to  $T_p + \Phi$ . This is shown in Figure 2.19.



As with the *e* budget there is a peak in shear production at z = h. Turbulent transport is only about a third of  $P_s$ , leaving a large residual, which is expected since it is the dominant dissipation term.  $T_t$  is a source term at all z > h, and a sink within the canopy. The magnitudes we see here for treatment **D** (PAI = 0.4) agree closely with those reported by BFR (PAI = 0.47). All terms in the shear stress budget decrease with decreasing density.

### 2.3.8.Quadrant-hole analysis

In quadrant analysis, the u'w' series is split into the quadrants of the u'-w' plane. These are labelled as outward interactions (I: u' > 0, w' > 0), ejections (II: u' < 0, w' > 0), inward interactions (III: u' < 0, w' < 0) and sweeps (IV: u' > 0, w' < 0). A normalised conditional stress is defined as

$$S_{i,H} = \frac{1}{\sigma_u \sigma_w} \frac{1}{T} \int_0^T u' w' I_{i,H} dt \qquad (2.14)$$

where T is the averaging time interval (20 s for this data), and  $I_{i,H}$  is an indicator function which is 1 when u'w' is in the  $i^{th}$  quadrant and  $|u'w'| > H\sigma_u\sigma_w$  and 0 otherwise. H is a dimensionless parameter called hole size. Note that often instead of the normalised stress, a stress fraction is calculated by replacing  $\sigma_u\sigma_w$  in (1) with  $\overline{u'w'}$ . This study has used the former (following RCL) because the normalisation allows comparison of flows with different correlation coefficients. A hole size, H', is also defined wherein half of the normalised momentum transport takes place, i.e.

$$\sum_{i=1}^{4} S_{i,H'} = \frac{1}{2} r_{uw}.$$
 (2.15)

With this H', the time fraction for half of the momentum transport can be calculated as:

$$t_{H'} = \frac{1}{T} \sum_{i=1}^{4} \int_{0}^{T} I_{i,H'} dt . \qquad (2.16)$$

Figure 2.20 shows the quadrant analysis at z/h = 0.73, 1.0, 1.67 and 3.93. Sweeps

clearly dominate in-canopy transport in all cases, with extreme events becoming increasingly farther from the mean as PAI increases. At z/h = 0.73, outward interactions also play a role, showing that occasionally faster air moves up from lower regions of the canopy. This has been observed before, as discussed by GGH, and they also report increasing positive contributions to total stress momentum with increasing density. Though not shown here, the contribution of the interactions increases with greater depth into the canopy. At z/h = 1 outward interactions are small, and the relatively large sweeps have diminished somewhat. Above the canopy (z/h = 1.67), sweeps and ejections are nearly equal and clearly stronger than the two interactions (which are also approximately equal). At z/h = 3.93 ejections have become dominant over sweeps (as expected from  $Sk_u$  and  $Sk_w$ ) indicating that this position is in the outer layer. Time fractions for half of momentum transport, shown in Figure 2.21a, merge to a constant value of about 8-9% above the canopy, as seen by RCL, LB and in Chapter 2. Within the upper canopy transport becomes more intermittent, with increasing density leading to increasing intermittency. Momentum transport occurs in very large and infrequent gusts, implying that eddies of smaller size are not important for transport. The lower half of the canopy apparently reverses the trend, though results there, especially in A, may be due to measurement error.

Profiles of H' and  $S_{4,0}/S_{2,0}$  (the ratio of sweeps to ejections) are shown in Figure 2.21b and c, respectively. Above the canopy, both quantities rapidly converge to near constant values, with H' around 2 and  $S_{4,0}/S_{2,0}$  at 1. Within the canopy increasing density leads to increased values for both variables. The high H' indicates that the large events responsible for 1/2 momentum transport are very far from the mean, and the high  $S_{4,0}/S_{2,0}$ indicates that sweeps form the dominant portion of momentum transport. GGH report  $S_{4,0}/S_{2,0}$  close to this study for their dense case (GGH4), while their thin case (GGH8) is lower than any treatment reported here. RCL claim that X-wire probes can cause overes-



timates of  $S_{4,0}/S_{2,0}$ , however the close agreement between GGH4 and this study suggest that this is not occurring with the triaxial probe. RCL report  $S_{4,0}/S_{2,0} \approx 1.3$  in their canopy of PAI = 0.23, which fits closely with the data presented here. It is unclear why GGH8 is lower than expected since the leaf area distribution would suggest higher values around z/h = 0.4 given the pattern shown here.



Figure 2.21: a) Hole size for 1/2 momentum transport. b) time fraction for 1/2 momentum transport. c) Ratio of sweeps to ejections.

	A (4.5)
<u> </u>	B (1.7)
	C (0.7)
•••••	D (0.4)
x	GGH4 (3.2)
+	GGH8 (0.8)

### 2.4.Discussion

This study is unique in having examined turbulent flow in a canopy of varying density in a wind tunnel. The results agree very well with results of GGH from the field.

This gives confidence that the wind tunnel results are applicable to real-world situations. The few disagreements between the present study and GGH are most likely due to hotwire probe errors. In particular, the probe underestimates higher-order statistics of w, which may also be related to the lack of observed inertial subrange in the w spectra. The uw co-spectra show large portions of transport occurring at higher frequencies, however the quadrant analysis indicated that large gusts were primarily responsible for momentum transport. This discrepancy points toward the probe overestimating high-frequency w.

Two important consequences of thinning a forest have been shown by this study. First, the amount of momentum absorbed by the forest did not change very much, and the amount absorbed by the floor increased only slightly as the canopy was thinned. This means that each tree experiences a greater force and moment as the forest thinned. Other factors being equal, this means the thinned forest should experience greater amounts of blowdown than the unthinned forest. In addition, turbulent energy increased in the thinned cases, and momentum transport became less intermittent (therefore more efficient). This means transport of scalars will increase significantly in thinned stands, and so affect the microclimate. In particular evaporative demand will increase as will temperature extremes (especially when changes to the radiation budget are also considered).

The *u* spectra clearly showed that the frequency of the energy containing eddies did not change with height or treatment. Linear stability theory predicted a changing  $u_c$ based on  $L_s = u_h/(\partial u/\partial z)|_h$ . However, visual inspection of the  $\overline{u}$  profiles showed  $L_s = h/2$ was a better estimate for all treatments. Using this  $L_s$  gave a  $u_c$  consistent with the measurements of Shaw *et al.* (1995) for the denser treatments, and suggested that  $u_c = 2u_h$ does not hold for thinner canopies. Measurements of  $L_u$  showed that above the canopy

the eddy size did not change with treatment, but that when the eddies penetrated the canopy they were broken down into eddies approximately as large as the canopy openings. GGH showed a similar result, as did RCL.

### **2.5.Conclusions**

This study has shown that canopy density strongly influences turbulent regimes. Thinning of forests through such practices as selective logging may have a negative impact on the forest. In particular, the microclimate will become harsher and blowdown of remaining trees more likely. However, these are influenced by many other factors, such as soil strength, tree structure and surface roughness, which also must be taken into account when considering alternative harvesting practices.

In addition, this study has shown that results from the wind tunnel generally agree with field studies. This is important not only for validating this study, but also for other studies conducted using the wind tunnel. It also shows that the triaxial probe is capable of measuring turbulent flows, with the caveat that higher-order w statistics and spectra may be inaccurate. In particular, it implies that the results of Chapter 3 concerning shelterbelts are relevant to the real-world.

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# 3.Wind Tunnel Study of Shelterbelt Flow: Comparison of Laminar and Turbulent Flow Regimes

### **3.1.Introduction**

Shelterbelts appear in a variety of agricultural and forestry situations. In particular, riparian zones (the area around stream beds) must be left uncut creating a narrow strip of vegetation, i.e. a shelterbelt. The width of these zones is regulated by the Forest Practices Code of British Columbia; this study is concerned with how the width affects the wind forces acting on the trees and the downwind turbulence regime. These are important issues for the survival of the standing trees, which are usually in shallow, wet soils and prone to blowdown, and for the downwind microclimate, which will influence regeneration of the cut area.

Our understanding of air flow downwind of windbreaks has improved significantly over the last few decades. Raine and Stevenson (1977) studied artificial fences of varying porosity in a wind tunnel and were able to demonstrate the importance of fence-top generated turbulence. Wilson (1985) showed excellent agreement between a second-order closure model for windbreak flows and measured first and second order turbulence statistics. Heisler and DeWalle (1988) and McNaughton (1988) together provided comprehensive reviews of the effects of windbreak structure on wind flow and the effects of windbreaks of leeward microclimate, respectively. Zhuang and Wilson (1994) examined coherent structures in windbreak flow and their role in momentum transport. Wang and Takle (1995) have also recently presented a model of flow around shelterbelts. An impor-

tant conclusion of these studies is that upstream turbulence greatly affects downstream characteristics and recovery. Further, while we have a firm understanding of simple two dimensional windbreaks, the full effects of structure, and in particular width, remain to be fully explored.

The objective of this study was to characterise the effects of shelterbelt width on downstream turbulence. This was accomplished using a wind tunnel model with 1, 2, 4 and 8 rows of model trees planted perpendicular to the flow. Measurements were taken with a fast-response hot-wire anemometer in both turbulent and laminar upstream flows. In this chapter turbulent statistics up to fourth moment are examined, as well as spectral data. These are discussed in relation to transport of momentum and turbulent energy to understand the development and recovery of downstream flows.

### **3.2.** Materials and Methods

### 3.2.1.Wind Tunnel

This experiment was carried out using the same wind tunnel and model trees as in Chapter 2. The wind tunnel, owned by the Department of Mechanical Engineering at UBC, had a working section 25 m long by 2.4 m wide by 1.5 m high. For this experiment, a constant windspeed (as measured by a pitot-manometer system at the front of the tunnel) of 8 m s<sup>-1</sup> was used. Measurements were made in both laminar and turbulent flows. For the laminar case the wind tunnel was empty except for the shelterbelts. For the turbulent case a flow simulating the atmospheric boundary layer in neutral conditions was generated by Counihan spires (Counihan 1969), bluff bodies (boards), and roughness elements

(wooden blocks) (Figure 2.1). Beyond the blocks the tunnel floor was smooth with the shelterbelts placed 10h (where h is tree height) downwind from the blocks. The peak turbulent energy downwind of the blocks is at 10h (Liu *et al.* 1995), so this location for the shelterbelts provided maximum contrast with the laminar case.

The co-ordinates used in this chapter are similar to Chapter 2, with z = 0 at the floor and y = 0 directly in the middle of the tunnel. The x position, however, is given in relation to the shelterbelts with negative indicating distance upwind from the leading edge and positive distance downwind of the trailing edge. Note that for reporting this squeezes the shelterbelts into two dimensions with no longitudinal extent, though the width of the shelterbelts is important when flow development over them is considered.

### **3.2.2.Instrumentation**

Cartesian wind vectors were measured using a 3D hot-film constant temperature anemometer (model 56C01, Dantec Electronik, Denmark). The probe (Model 55R91) had three orthogonal sensing fibres each at 54.7° to the probe axis, giving an acceptance cone of 70.6°. Calibration of the probe was performed following Jørgensen (1971), who described the effect of pitch and yaw on the signal from a single hot-wire. Full details of the calibration procedure are in Appendix I.

Voltage signals from the probe were recorded using a 486-based PC with an A/D board (Multi-functional carrier PCI-20098C-1, Intelligent Instrumentation, USA). At every sampling location signals from the 3 probe wires were recorded for 20 s at 500 Hz, creating raw voltage files of  $3 \times 10,000$  data points. Data was 'streamed' directly onto a hard disk drive and later transferred to optical disks. Processing of the data was done

from the optical disks by first converting the raw voltage signals into velocity vectors in hot-wire co-ordinates, then performing a transformation to shift to wind-tunnel coordinates. Mean velocities  $(\overline{u}, \overline{v} \text{ and } \overline{w})$  and fluctuations (u', v' and w') were then calculated, where u, v and w are the streamwise, cross-stream and vertical components, respectively.

### **3.2.3. Model Trees and Shelterbelts**

The model shelterbelts consisted of individual model trees inserted into drilled holes in sheets of  $1.2 \times 2.4$  m plywood. Hole spacing equalled tree breadth, and rows were staggered. The trees, composed of plastic strips with an interwound steel wire trunk, were 15 cm tall and 4.5 cm wide. They were made using materials supplied by a Christmas tree manufacturer (Barcana, Granby, Canada). Foliage was completely removed on the lowest 1.5 cm to simulate a branch-free 'trunk' space and the upper portion of the trees was trimmed to a conical shape, giving the per tree plant area profile in Figure 2.2.

Four widths were used in this study: 1, 2, 4 and 8 rows. All were studied in both laminar (L) and turbulent (T) flow, so each case will be denoted by the number of rows and either T or L (e.g., 8L is the eight row break in the laminar tunnel). Also included in this study are measurements made in the turbulent tunnel with no windbreak, denoted 0T.

Following Wang and Takle (1995), the resistance coefficient  $(k_r)$  was estimated as

$$k_r = \int_0^h C_d a(z) dz \,. \tag{3.1}$$

The drag coefficient  $(C_d)$  was estimated using a force/moment balance which measures

force and moment independently. Measurements were made on trees placed in 1 and 2 row breaks in laminar flow. This led to a range of  $C_d$  from which 0.75 was taken as a typical value. The leaf area density a(z) was calculated for each shelterbelt as the total leaf area divided by the volume occupied by 1 row of trees at each z. This produced  $k_r = 10$ , 20, 40 and 80 for the 1, 2, 4 and 8 row breaks, respectively.

Profiles consisted of 16 vertical measurement points at z = 2, 3, 5, 7,..., 25, 35, 45and 60 cm (z/h = 0.13, 0.2, 0.33, 0.47,..., 1.67, 2.33, 3 and 4). Profiles were sampled at x/h = -1.0 and -0.3, and at x/h = 0.3, 1.0, 1.5, 3, 6, 9 and 18. Not all x positions are shown in this chapter to avoid overly complicated figures. In the laminar case, an additional profile was also measured at x/h = 36. Measurements were also made at the eight z > h positions just above the back row of each windbreak. For the one, two and four row cases, the first three positions downwind were measured at two locations – directly behind a tree and in between the trees in the last row (Figure 3.1). Profiles at these positions were calculated as a simple average of the two locations.



Figure 3.1: Overhead view of shelterbelt measurement positions.

## 3.3.Results

### 3.3.1.Mean Velocities

Profiles of  $\overline{u}$  for both laminar and turbulent cases are shown in Figure 3.2. In the turbulent case the different widths have similar effect, though reduction immediately leeward increases slightly with shelter width. By 9h the profiles have returned to their -1h values. This demonstrates the similarity between flow downwind of the blocks and the shelterbelts since the -1h profiles are 9h downwind of the blocks.

Because  $\overline{u} = 0$  at z = 0, there is a clear secondary maximum near the floor, where wind blows through the trunk space. This feature disappears by 6h downstream. There is speed-up right over the shelter, indicated by the bump near z = h in the x = h profiles. The effect of the shelterbelts on windspeed extends only up to z = 2h, and this decreases with distance downstream.

In the laminar case the shelterbelts exhibit a much stronger relative effect on mean wind, with greater difference between treatments. The reduction of  $\overline{u}$  extends beyond x =18*h* and above z = 3h, and at x = 36h there is still not full recovery of the upstream profile (which changes only slightly with x in the empty tunnel). There is strong speed-up over top of the shelter and clear blow-through near the floor. As the shelter widens there is an increase in magnitude of leeward reduction and break-top speed-up as well as in horizontal and vertical extent of effect. Qualitatively, both laminar and turbulent cases exhibit similar features, however the laminar case exaggerates the effects.



In both laminar and turbulent cases the  $\overline{u}$  profiles at x/h = 1 have many features in common with canopy profiles and mixing layers (Chapter 2, Raupach *et al* 1989). Around z/h = 0.5,  $\overline{u}$  becomes nearly constant with z, and in the laminar case  $\overline{u}$  becomes constant

above z/h = 1.5. There is a clear inflection point near z/h = 1 as seen in mixing layers and the canopy profiles of Chapter 2.

Vertical wind shear  $(\partial u/\partial z)$ , calculated by finite difference, is shown in Figure 3.3. The turbulent case is similar for all treatments, with 2T and 4T having somewhat larger



gradients at x = z = h, the region of maximum shear for all treatments. The gradients peak at about 50 s<sup>-1</sup>, in contrast to the laminar case where gradients are well over 100 s<sup>-1</sup>. 2L creates the strongest shear extending to 18*h* downwind. 8L exhibits the weakest gradient with the shortest horizontal extent, though it is still twice that of the turbulent cases. This is so despite the fact that 8L has the greatest leeward reduction of  $\overline{u}$ . This is because of the horizontal extent of the 8 rows which drags on the flow and reduces  $\overline{u}$  above z = h, thereby reducing the gradient.

### **3.3.2.Turbulence Statistics**

### **3.3.2.1.** Momentum transport

Figure 3.4 shows profiles of momentum transport  $\overline{u'w'}$ . In the turbulent case the treatments all have similar profiles with no significant differences except for 8T at x = h, where  $\overline{u'w'}$  is smaller from z/h = 1.5 to 3.5. This is due to the drag of the 8-row break, which is developing a boundary layer and beginning to act like a full forest. The maximum transport occurs at x = 3h where the profile resembles  $\overline{u'w'}$  profiles seen in mixing layers (Raupach *et al* 1989). Throughout much of the measurement region above z = h,  $\overline{u'w'}$  maintains fairly constant values around  $-0.5 \text{ m}^2 \text{ s}^{-2}$ , just as seen above the canopies in Chapter 2. Within the sheltered zone  $\overline{u'w'}$  shows positive values for all treatments. This extends past 3h downwind, except for 8T, and is due to blow-through from the 'trunk' region of the shelterbelts. The profiles still show a peak at z = h out to x = 9h, which is not seen downwind of the blocks.



As expected, the laminar case profiles have  $\overline{u'w'} = 0$  upwind, except for a small boundary layer near the floor, and remain zero where the flow is still laminar downwind of the shelter. The maximum values do not develop until 9 to 18*h* downwind, where the

peaks are much greater than in the turbulent case. The maximum also increases in magnitude as the shelterbelts widen. The profiles from 3 to 18*h* closely resemble mixing layer profiles, with the maximum  $\overline{u'w'}$  developing downwind of the maximum shear. This shows the time necessary for the shear to develop into turbulence. For  $\overline{u}$  in this region of about 5 m s<sup>-1</sup>, the shear takes approximately 1/3 s to develop from the windbreak to the point of maximum  $\overline{u'w'}$ . There are positive values in all treatments near the floor, expanding out from z/h = 0 to between 3 and 9*h* downwind. The area of positive  $\overline{u'w'}$  is largest in 1L, where the trunk space is most porous.

### 3.3.2.2.TKE

Profiles of turbulent kinetic energy  $(e = \frac{1}{2}\sigma_i^2)$ , where Einstein summation is used) are shown in Figure 3.5. These plots bear a strong resemblance (but reversed in sign) to the  $\overline{u'w'}$  plots, indicating a close relationship between momentum transport and e. Both graphs share many of the same features, including the constancy of e across turbulent treatments, and the increase in e with break width in the laminar cases. In fact, 8L has a peak e nearly 40% greater than the turbulent cases. 8T shows a reduction of e above z/h= 1.5 in the 1h profiles due to the drag of the wide shelterbelt.



Figure 3.6 shows the percent change in e from 0T to the turbulent break cases calculated by interpolating values from the 0T case to the actual x positions measured in each shelter treatment. For each treatment there is a region of increasing e extending out from

the top of the break; however, the peak is at 9*h* downwind, while in the laminar cases the peak is 18*h* downwind of the break. The vertical extent of *e* is also much greater in the laminar cases. The turbulent-tunnel pattern, with a peak increase in *e* centred around x/h = 10, has been also been reported by Finnigan and Bradley (1983), Raine and Stevenson (1977) and simulated by Wilson's (1985) model. These plots show a triangular zone of reduced *e* extending approximately from the top of the shelterbelts to the floor at 9*h*, as described by Wilson (1985) and McNaughton (1988). This is the quiet zone; the wake zone, where *e* is enhanced near z = 0 by shelter-generated turbulence, is at  $x \ge 9h$ .



Figures 3.7a, b, c and d show profiles of the dominant terms of the e budget (Raupach and Shaw 1982). Shear production (Figure 3.7a) is defined

$$P_{s} = -\overline{u_{i}^{\prime}u_{j}^{\prime}}\frac{\partial u_{i}}{\partial x_{j}}, \qquad (3.2a)$$

which can be simplified by assuming that the lateral components are negligible. This leaves

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$$P_{s} = -\overline{u'^{2}} \frac{\partial \overline{u}}{\partial x} - \overline{u'w'} \frac{\partial \overline{w}}{\partial x} - \overline{u''w'} \frac{\partial \overline{u}}{\partial z} - \overline{w'^{2}} \frac{\partial \overline{w}}{\partial z}$$
(3.2b)

where the horizontal gradients were found to be generally an order of magnitude smaller than the vertical, and the third r.h.s. term was estimated to be at least 3 times the last term. Thus, shear production has been estimated using just the third r.h.s. term above (as it is done for horizontally homogeneous cases).

Turbulent transport (Figure 3.7b) is given by

$$T_t = -\frac{\partial \overline{u_j' e}}{\partial x_j} \tag{3.3}$$

where we can again assume the y component to be negligible and the vertical gradient much larger than the horizontal gradient.

Dissipation (Figure 3.7c) was estimated from the spectra according to Kolmogorov's hypothesis

$$fS_{uu}(f) = \alpha_{u} \varepsilon^{2/3} (2\pi f / \bar{u})^{-2/3}$$
(3.4)

with  $\alpha_u = 0.55$  (after Brunet *et al.* 1994) and the inertial subrange assumed to be 30 to 120 Hz for all positions. The figures show that the largest  $\varepsilon$  occurs with the peak  $P_s$ , and that  $\varepsilon$  and  $P_s$  are in approximate balance throughout much of the measurement area.

The residual (Figure 3.7d) should be composed mostly of pressure transport  $(T_p)$ , with some wake production  $(P_w)$  immediately leeward of the break. The residual is close to 0 throughout much of the measurement region, and generally follows  $T_t$  in magnitude, which is expected if it is composed mostly of  $T_p$ .








# **3.3.2.3.**Correlation Coefficient

Plots of the correlation coefficient  $(r_{uw} = \overline{u'w'}/\sigma_u \sigma_w)$  are shown in Figure 3.8. Because  $r_{uw}$  is undefined in laminar flow, the plots exclude regions with  $I_u < 5\%$  (where



 $I_u = \sigma_u / \overline{u}$  is the turbulent intensity). In the turbulent tunnel  $r_{uw}$  is nearly constant above z = h at -0.35 to -0.4, which is typical of atmospheric surface layer values. The only deviations are within the sheltered zone behind the breaks, where there is a drop in magnitude. This indicates that turbulence is not efficiently transporting momentum in this region. The profiles at x = h closely resemble those in the canopy flows of Chapter 2. In the laminar case, the areas where  $r_{uw}$  is defined resemble the turbulent case with positive values near the floor and development at greater z to a fairly constant value around -0.4. However, the positive region is much larger, particularly for the narrower shelterbelts. At x = h,  $r_{uw}$  does not have a clear value or pattern, but is around zero for all treatments. This indicates a lack of structure in the turbulence until 3h downwind.

### 3.3.2.4.Skewness and Kurtosis

Skewness of horizontal and vertical velocity components  $(Sk_i = \overline{u_i'}^3 / \sigma_i^3, i = u$  and w, respectively) is shown in Figure 3.9a and b. In the turbulent case,  $Sk_u$  (Figure 3.9a) crosses zero at about z = 2h throughout the measurement region – not only in the shelter treatments but also in the 0T case (not shown). Above 2h it is negative and below positive. The largest values occur immediately leeward of the breaks and adjust back toward upwind values by 9h. As with the  $\overline{u}$  profiles, this demonstrates similarity between the flow downwind of the blocks and downwind of the shelter, despite the differences in extent and porosity. Beyond 9h there is little development of these profiles. The profiles at 1h and 3h have the same shape and magnitude as canopy profiles with 1h resembling a

denser canopy (see Chapter 2).

In the laminar case, upstream values (theoretically undefined but practically calculable) are around zero except for a large peak between z/h = 0.5 and 1. This is not an ef-



fect of the shelterbelts, it also appears in profiles measured with the wind tunnel completely empty. It is due to the mixing of the floor boundary layer with the flow higher up. As with the turbulent case, downstream of the shelter there is a positive peak in the  $Sk_u$ profiles, however it does not develop until 3h downwind and it is still visible at 18h. Above z = h downwind of the shelter there is a region of strongly negative values which moves higher as x distance increases. This is the border of the turbulent layer created by the shelterbelts, similar to the peak above the floor boundary layer, and its rise shows the development of the layer. As with  $\overline{u}$  and  $\overline{u'w'}$ , the  $Sk_u$  profiles show a strong resemblance to a mixing layer. In a typical mixing layer,  $Sk_u$  is positive towards the slower stream and negative towards the faster stream (Raupach *et al.* 1989). This is seen from x/h = 1 to 18, with the zero-crossing at z/h = 1, as expected since the inflection point is also there.

The  $Sk_w$  profiles (Figure 3.9b) share many characteristics of  $Sk_u$  with the sign reversed. In the turbulent case, however, rather than negative values behind the shelter, as in a canopy, there are negative values near z = h and positive lower down right behind the shelter. This is due to faster air blowing through the trunk space. The positive values disappear by 3h, and the profiles adjust to upstream values by 6h downwind. The laminar case profiles of  $Sk_w$  are very much like the  $Sk_u$  profiles, though the upstream peak is not as large in magnitude. As discussed in Chapter 2,  $Sk_w$  may be underestimated by the probe.

Kurtosis of horizontal and vertical velocity components  $(Kr_i = \overline{u_i'}^4 / \sigma_i^4, i = u \text{ or } w,$ respectively) is shown in Figure 3.10a and b. The turbulent case profiles show a value of 3, consistent with a Gaussian normal distribution, throughout most of the measurement



region, except right behind the shelter to x = 3h. 8T shows a more peaked distribution extending farther, while as the shelter narrows  $Kr_u$  decreases and quickly returns to 3.



The laminar case profiles are quite similar to  $Sk_u$ , with a peak between z/h = 0.5 and 1 upstream and the boundary between the turbulent layer and the laminar layer indicated by

 $Kr_u > 3$  in the upper measurement region.  $Kr_w$  shares the same features as  $Kr_u$  with the caveat from Chapter 2 that actual magnitudes may be underestimated.



# 3.3.2.5.Integral Length Scale





$$L_{i} = \frac{\left\langle \bar{i} \right\rangle}{\sigma_{i}^{2}} \int_{0}^{\tau_{0}} \overline{i'(t)i'(t+\tau)} d\tau \qquad (3.5)$$

where i = u or w,  $\tau$  is time lag and  $\tau_0$  is the first zero-crossing of the autocovariance function. Though this scale should only apply to cases of isotropic, stationary, homogenous turbulence, it is found to provide useful information when not all of these conditions are met. The plots have been normalised by h to facilitate comparison with other studies. For laminar flow,  $L_u$  is undefined and so is not calculated where ever  $I_u < 5\%$ .

At large z in the turbulent profiles,  $L_u/h$  maintains steady values around 2 to 2.5, as found above the model forests in Chapter 2. Right behind the shelter,  $L_u$  drops to small values, as it does within a canopy. At 18*h* downwind of the breaks, the profiles are generally straight, indicating that away from the breaks and roughness elements  $L_u$  is independent of z. Again the profiles at 9*h* replicate those upwind, showing similarity between flow downwind of the shelter and downwind of the blocks. There is no systematic difference in  $L_u$  with treatment in the turbulent case.

In the laminar case,  $L_u$  is very small behind the shelter out to 18*h* downwind. The turbulence generated by the shelter is at a small scale, and it is not until the shear produced turbulence begins to dominate that the eddies develop to order *h*. At large *x*, 1L produces somewhat smaller eddies, while the other 3 treatments produce larger eddies of about the same size.

The vertical length scale  $L_w$  bears a strong resemblance to  $L_u$  with magnitudes on the order of  $0.3L_u$ . In addition,  $L_w$  shows an upwind peak in the turbulent case around z = h, showing vertical structure develops as the air begins to be forced up over the break. In the laminar case there are relatively large values for  $L_w$  at the top of the downwind turbulence region, indicating vertically coherent motions. These structures have  $L_w \approx L_u$ , which is not seen in canopy flow.



### 3.3.3.Spectra

Spectra were computed for all data based on Welch's method using an FFT and a Hanning window (Matlab Signal Processing Toolbox, The MathWorks, Inc.). This method smoothes the high frequency signal at the expense of some of the low frequency signal. Due to difficulties in presenting a large number of spectra only selected positions are shown from the 1 and 8 row cases (in both turbulent and laminar flow). In the turbulent case (Figure 3.12a and b) the u spectral peak tends to shift to higher frequency behind the breaks, as reported by Raine and Stevenson (1977) and Zhuang and Wilson (1994). though here it shifts only by about a factor of at most 2. The spectral peak adjusts back to upstream values in 3 to 6h. The spectral energy right behind the breaks at z/h = 0.5 also drops considerably, and does so more as the shelterbelt widens. The peaks do not change with width. All spectra show a clear inertial subrange spanning about a decade. At z/h =1, x/h = 1 and 3 and at z/h = 0.5, x/h = 3 the ratio of lower frequency energy (near the peak) to higher frequency increases, showing that larger motions are quite important in the lee of the shelterbelt even if smaller than their upwind counterparts. There is a decrease in the energy content behind the break at z/h = 0.5: x/h = 1 and 3, followed by full recovery. From 9h to 18h there is a decrease again in spectral energy due to dissipation of turbulent energy.

In laminar flow spectra are zero, but within the turbulent regions there is a shift by about a factor of up to 10 to lower peak frequencies as one moves downwind. The peaks are initially at higher frequencies in the 1L case than in the 8L, and the 8L spectra are broader than 1L. The spectra downwind in the 8L case have somewhat higher peak frequencies than the turbulent cases. The decrease in peak frequency with x is greater in the laminar cases, though it happens just as quickly. In the laminar case there is more energy right behind the 1L case than further downwind, which is related to blow-through due to its relatively high porosity. An inertial subrange usually develops by 3h downwind. It is not as broad as in the turbulent case, though it grows as x increases. The spectra fall off faster at the higher frequencies than the expected -2/3 slope. By 6h the laminar spectra begin to resemble the turbulent spectra. In the 8L case the energy is greatest at x/h = 18, where the ratio of energy in the lower to higher frequencies is greater than seen elsewhere. In all laminar treatments there is less energy in the very lowest frequencies than in the turbulent treatments.

Spectra of the *w* component are shown for the same positions as above in Figure 3.13a to d. In general, these resemble the *w* spectra seen in Chapter 2, with large amounts of energy in the high frequencies and no -2/3 slope. As discussed in Chapter 2, the high frequency energy in these spectra may be due to probe error. At z/h = 0.5 the energy drops behind both breaks and recovers to upstream values in 3 to 6*h*. Here there is little change from 6 to 18*h*. As with the *u* spectra, there is an increase in the ratio of lower to higher frequency energy, seen at both heights at x/h = 3 and 6 in the 1T case, and at z/h = 1:x/h = 1, 3 and 6 in the 8T case.

For the 1L case there is a very strong high frequency signal in w at x/h = 1, though there is very little energy for 8L. In both laminar cases there is little low frequency, though there is more in the 8L case. By 18h downwind, the 8L case has generated spectra that closely resemble spectra from the turbulent tunnel. As with u, the w spectral energy in the 8L case increases with x with a maximum at 18h and a decrease after that. In the 1L case the high frequency peaks at x/h = 1 and decreases with x, though the low frequency increases somewhat with x.

The u'w' co-spectra, shown in Figure 3.14a to d, all closely resemble the *w* spectra, indicating a close relationship between *w* fluctuations and momentum transport. Of particular note is the large amount of energy in the 8L case at x/h = 18, where the maximum  $\overline{u'w'}$  and  $P_s$  were found. However, as discussed in Chapter 2, the *w* spectra may contain errors which also contaminate the u'w' spectra.



Figure 3.12a: Spectra of u component for 1T at z/h = 1 (top) and z/h = 0.5 (bottom).























Figure 3.13c: Spectra of w component for 1L at z/h = 1 (top) and z/h = 0.5 (bottom).



Figure 3.13d: Spectra of w component for 8L at z/h = 1 (top) and z/h = 0.5 (bottom).







Figure 3.14b: Co-spectra of u'w' for 8T at z/h = 1 (top) and z/h = 0.5 (bottom).



Figure 3.14c: Co-spectra of u'w' for 1L at z/h = 1 (top) and z/h = 0.5 (bottom).



Figure 3.14d: Co-spectra of u'w' for 8L at z/h = 1 (top) and z/h = 0.5 (bottom).

# 3.3.4.Quadrant-hole analysis

In quadrant-hole analysis the u'w' series is split into quadrants of the u'-w' plane. These are labelled as outward interactions (I: u' > 0, w' > 0), ejections (II: u' < 0, w' > 0), inward interactions (III: u' < 0, w' < 0) and sweeps (IV: u' > 0, w' < 0). A normalised conditional stress is defined as

$$S_{i,H} = \frac{1}{\sigma_u \sigma_w} \frac{1}{T} \int_0^T u' w' I_{i,H} dt \qquad (3.6)$$

where T is the averaging time interval (20 s for our data), and  $I_{i,H}$  is an indicator function which is 1 when u'w' is in the  $i^{th}$  quadrant and  $|u'w| > H\sigma_u\sigma_w$  and 0 otherwise. Here H is a dimensionless parameter called hole size. Often a stress fraction is calculated instead of the normalised stress by replacing  $\sigma_u\sigma_w$  in equation (3.6) with  $\overline{u'w'}$ . The former has been used here (following Raupach *et al.* 1986) because it allows comparison between regions of very different correlation coefficients. A hole size, H', is also defined wherein half of the normalised momentum transport takes place, i.e.

$$\sum_{i=1}^{4} S_{i,H'} = \frac{1}{2} r_{uw} ..$$
(3.7)

Typical values for H' above a canopy are around 2 (Raupach *et al.* 1986, Chapter 2). This analysis is undefined in laminar flow, and so has been left uncomputed where  $I_{\mu} < 5\%$ .

Figure 3.15 shows profiles of the ratio  $S_{4,0}/S_{2,0}$  (sweeps to ejections). As expected, the turbulent case profiles bear a strong resemblance to  $Sk_u$ , with the zero-crossing of  $Sk_u$ at z/h = 2 matching  $S_{4,0}/S_{2,0} = 1$ . Behind the breaks sweeps become much more dominant, with  $S_{4,0}/S_{2,0}$  increasing with shelter width. This extends some distance downstream, being still noticeable at x/h = 18. A similar dominance of sweeps is seen within canopies, and follows from the fact that free stream momentum penetrates in gusts into the sheltered zone.



The laminar case profiles of  $S_{4,0}/S_{2,0}$  do not closely match the laminar  $Sk_u$  profiles, but they do have features in common with the turbulent  $S_{4,0}/S_{2,0}$  profiles. Sweeps are

strongly dominant behind the breaks (though again the laminar cases have a farther reaching effect). These plots show the importance of ejections at the top of the turbulent zone, particularly far downwind at x/h = 36 where  $S_{4,0}/S_{2,0} < 0.5$ . These profiles demonstrate that behind the laminar breaks transport is dominated by downward gusts of faster air, while the mixing at the turbulent/laminar boundary is dominated by updrafts of slow air.

Figure 3.16 shows that H' is about 2 (as seen above the canopies in Chapter 2) everywhere in the turbulent tunnel except in the sheltered zone. The high H' values there are indicative of very infrequent gusts which differ by many standard deviations from the mean. These gusts are responsible for large portions of momentum transport in this region. In the laminar case, the shelter produces values in the downstream turbulence which are a bit larger on average than 2, but fall to 2 by 36h downstream. A feature of note is the region of large H' at the top of the turbulent zone which indicates very intermittent transport at the border between the laminar and turbulent flows.



### **3.4.Discussion**

Flow downwind of shelterbelts was shown to resemble a turbulent mixing layer. This was demonstrated by the  $\overline{u}$ ,  $\overline{u'w'}$  and  $Sk_i$  profiles, all of which displayed characteristics typical of a mixing layer with an inflection point in  $\overline{u}$  at z = h. In the turbulent case, mixing layer characteristics were limited to a region less than 0.5h in vertical extent (centred at z = h) and reaching at most to x = 6h. The resemblance in the laminar case was clearer, and extended to 18h downwind. The spectra from the laminar case far downwind resembled spectra from the canopies of Chapter 2, the main difference being that  $f_p$  from the laminar shelter case was higher at 8 Hz. Given the apparent success of linear stability theory in describing the data in Chapter 2,  $L_s \approx 0.05$  m was visually estimated from the laminar case  $\overline{u}$  profiles at x/h = 1. This gives (from equation 2.9)  $u_c \approx 6$ m s<sup>-1</sup>, which is a typical wind speed in the region of large e. Though in itself this is not evidence that linear stability theory correctly describes shelterbelt flows, it is in agreement with Zhuang and Wilson (1994), who concluded that turbulence downstream of a wind break was dominated by coherent structures similar to those found in a mixing layer.

The quiet zone in the turbulent case, defined as the region of reduced e leeward of the shelterbelt, was seen to extend from the shelter top to the floor at  $x/h \approx 9$ , in agreement with previous studies (Wilson 1985, McNaughton 1988). This is also about where the windspeed near the floor returned to its upstream value. This region showed very intermittent transport (seen in  $Sk_i$  and  $Kr_i$ , as well as in the quadrant analysis), particularly near the top where mixing took place.

In the turbulent case the e budget showed  $P_s$  occurs in a vertically narrow band

close to the shelter. In contrast, the laminar case showed  $P_s$  occurs in a broader region. which widens with increasing x. Both cases lend support to Wilson's (1985) assertion that the downstream increase in e is due to an increase in  $P_s$ . Turbulent transport is moving eaway from those areas where  $P_s$  is strong source. Elsewhere in the turbulent case  $T_t$  is a weak source, except along the border of the shelter zone, where it is a relatively strong source of e. In the laminar case  $T_t$  is a sink in the region of strong production and acts to move e both up and down. In the laminar case dissipation is stronger towards the floor, indicating that higher up the transport terms - which account for the mixing of the turbulent and laminar regions – act as the main sink for e. The residual showed that  $P_s$  and D are roughly in balance throughout much of the region. The residual is most likely composed mostly of  $T_p$ , which mostly follows  $T_t$  in shape and magnitude, except that it is not a source along the border of the quiet zone in the turbulent case. This may be due to  $P_w$ roughly balancing  $T_p$  in this region, just as the positive values of the residual at x/h = 1 in the laminar case are probably due in part to  $P_w$ . The 1 to 3h downwind positions in the turbulent case resemble canopy profiles, as do the 9h laminar profiles. This shows both the time necessary for the development of the shear-generated turbulence, and the higher windspeeds in the laminar case. The turbulent case profiles all show their maximum values at x = h and decrease with x after that, while in the laminar case the values increase with x to maximum values around x/h = 18.

The results show that, in the turbulent case, vertical transport is taking place continuously everywhere but in the quiet zone. Quadrant analysis shows that below z = 2htransport is dominated by faster air moving down, and above that by slower air moving up. The laminar case exhibits very uneven motion and transport, with large skewnesses and kurtoses dominating in the regions bordering the break-generated turbulence. In the upper portions of the measurement area, this shows as intermittent spikes of slow air occasionally ejecting up into the laminar flow area. In the region separating the quiet zone from the break-top generated turbulence the opposite occurs, with spikes of fast air moving downwards. The net effect in all cases is downward momentum transfer. In the turbulent case momentum transfer is a relatively even and steady process while in the laminar case exchange is very uneven in both time and magnitude.

#### **3.5.**Conclusions

Upstream turbulence has a strong influence on downwind flow. It acts to reduce wind speed gradients and mix downwind flows, thereby reducing differences between treatments. This means that in a turbulent environment shelterbelt width is not significant for downstream flow in the clearing, and therefore will not exert much influence on microclimate there.

#### **3.6.Literature Cited**

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## **4.Conclusions**

This study has shown that turbulence regimes in the forest are strongly influenced by the density of the forest. As trees are removed from the forest, windspeed within the canopy increases, as does turbulent energy. This will cause greater transport of scalars, leading to increased evaporative demand and greater extremes in temperature. On the other hand, it was shown that the width of a shelterbelt has little affect on downstream conditions when the approach flow is turbulent (as is found in the real-world). This is due to the greater mixing caused by the turbulence.

Linear stability theory was shown to be capable of describing the length scales of the high energy eddy motions present in canopy flow, and possibly in shelterbelt flow as well. This is due to the strong influence of the shear generated turbulence caused by the presence of trees. The trees act to create a steep gradient in mean windspeed which is unstable, just as found in a turbulent mixing layer.

An important outcome of this study is that the wind tunnel model and triaxial probe have been shown to produce results which closely resemble field results under similar conditions. This means that results from the wind tunnel can be extrapolated to the real-world with a fair degree of confidence. This is important for future studies which will test situations that can not be verified directly in the field.

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## Appendix

## **Calibration of Dantec Triaxial Probe**

This study used a Dantec triaxial hot-film sensor (type 55R91) to measure wind speed components at high frequency. Calibration of the probe was done following Jørgensen (1971) and Bruun (1995), who described the effects of approach angle on sensor response and applied it to triaxial probes.

The basic relationship between windspeed and voltage output for any hot-wire is

$$U_{eff}^{2} = \left(\frac{V^{2} - V_{0}^{2}}{B}\right)^{2/n}$$
(A.1)

where  $U_{eff}$  is the effective cooling velocity, V the voltage signal,  $V_0$  the voltage at U = 0, and B and n are factors determined by the calibration process.  $V_{0i}$ , where i denotes wire number, was measured with the probe in its protective box at a range of ambient air temperatures. There is a strong linear relationship between  $V_{0i}$  and air temperature that was described by linear regression. For the probe used, the relationships are:

$$V_{01} = 1.4126 - 0.00491 T$$

$$V_{02} = 1.295 - 0.00368 T$$

$$V_{03} = 1.450 - 0.00659 T$$
(A.2)

where T is temperature in °C.

The effective cooling velocity is related to the wind vectors in wire co-ordinates by

$$U_{eff}^{2} = U_{x}^{2} + k_{1i}^{2}U_{y}^{2} + k_{2i}^{2}U_{z}^{2}$$
(A.3)

where  $k_{1i}$  is the yaw factor and  $k_{2i}$  the pitch factor. Co-ordinates are defined for each wire such that  $x_i$  is perpendicular to the wire and parallel to its arms,  $y_i$  along the length of the wire and  $z_i$  perpendicular to the  $x_i - y_i$  plane. Also defined are the angles  $\alpha_i$  and  $\theta_i$ , where  $\alpha_i$  is the angle of the  $x_i - z_i$  plane to the wind and  $\theta_i$  is the angle of  $x_i - y_i$  plane to the wind. The probe is designed such that when it is level with wire #3 vertical (tilt  $\beta = 0^\circ$ , rotation  $\omega = 0^\circ$ ),  $\alpha_i = \theta_i = 35.3^\circ$  for all three wires.

Jørgensen (1971) derived equations for the pitch and yaw factors such that when  $\theta_i$ 

$$k_{1i} = \frac{1}{\sin \alpha_i} \left[ \left( \frac{V_i(\alpha_i)^2 - V_{0i}^2}{V_i(0)^2 - V_{0i}^2} \right)^{2/n_i} - \cos^2 \alpha_i \right]^{1/2}$$
(A.4)

and when  $\alpha_i = 0^\circ$ ,

$$k_{2i} = \frac{1}{\sin \theta_i} \left[ \left( \frac{V_i(\theta_i)^2 - V_{0i}^2}{V_i(0)^2 - V_{0i}^2} \right)^{2/n_i} - \cos^2 \theta_i \right]^{1/2}.$$
 (A.5)

For the triaxial probe, the equations form a linear system from which the wind components are determined in terms of cooling velocities by matrix inversion. This yields

$$\begin{cases} U_x^2 \\ U_y^2 \\ U_z^2 \end{cases} = \begin{cases} k_{11}^2 & 1 & k_{21}^2 \\ k_{22}^2 & k_{12}^2 & 1 \\ 1 & k_{23}^2 & k_{13}^2 \end{cases}^{-1} \begin{cases} U_{eff,1}^2 \\ U_{eff,2}^2 \\ U_{eff,3}^2 \end{cases}$$
(A.6)

where x, y and z are now co-ordinates defined by the orthogonal wires and  $k_{1i}$  and  $k_{2i}$  are different for each wire.

To fully calibrate the probe, a series of measurements was made in a laminar wind tunnel with the probe oriented in various positions (Table A.1). Wind speed was measured independently by a pitot tube and manometer system. Each position was sampled at windspeeds ranging from 2 to 16 m s<sup>-1</sup>, and signals recorded from all three wires. The first position was with the probe in its normal sampling position ( $\beta = 0^{\circ}$ ,  $\omega = 0^{\circ}$ ). The probe was then tilted down to  $\beta = -35.3^{\circ}$  so that wire #3 became normal to the wind with  $\theta_3 = 45^{\circ}$ . Next the probe was rotated about its axis 120° so that  $\alpha_2 = 0^{\circ}$  and  $\theta_2 = 45^{\circ}$ . The probe was then rotated again to  $\alpha_1 = 0^{\circ}$  and  $\theta_1 = 45^{\circ}$ . The next three positions began with  $\beta = +54.7^{\circ}$  and  $\omega = 0^{\circ}$ . This brought wire #2 to 'true' normal ( $\alpha_2 = 0^{\circ}$  and  $\theta_2 = 0^{\circ}$ ) and aligned the other wires such that  $\alpha_1 = 0^{\circ}$ ,  $\theta_1 = 90^{\circ}$ ,  $\alpha_3 = 90^{\circ}$  and  $\theta_3 = 0^{\circ}$ . Rotating the probe 120° counter-clockwise brought wire #1 to 'true' normal, and one more 120° rotation brought wire #3 to 'true' normal. Due to probe geometry, the truly normal wire in the  $\beta = 54.7^{\circ}$  position experiences interference from the other wires. This was demonstrated by turning off the power to the other two wires, which did not change the signal

from the active wire, showing that this is an air flow disruption effect rather than an effect of heat from the other wires.

Position	$\alpha_1$	θ1	α2	θ2	α3	θ <sub>3</sub>
$\beta = -35.3^{\circ}$ , wire #1 vertical	0°	45°	45°	0°	45°	90°
$\beta = -35.3^\circ$ , wire #2 vertical	45°	90°	0°	45°	45°	0°
$\beta = -35.3^{\circ}$ , wire #3 vertical	45°	0°	45°	90°	<b>0°</b>	45°
$\beta = 54.7^{\circ}$ , wire #1 normal	0°	0°	90°	0°	0°	90°
$\beta = 54.7^{\circ}$ , wire #2 normal	0°	90°	0°	0 <u></u>	90°	0°
$\beta = 54.7^{\circ}$ , wire #3 normal	90°	0°	0°	90°	0°	0°

Table A.1: Angles to wind for each wire in each position.

An initial estimate of *n* was first determined from equation (1). For this, the data from the level position was used. For each wire a linear regression of  $\ln(V^2 - V_0^2)$  against  $\ln(U)$  was calculated, with *U* measured by the pitot-manometer system used in place of  $U_{eff}$ . The slope of the line was equal to *n* for each wire.

With *n* and the data from the tilting and turning of the probe,  $k_{1i}$  and  $k_{2i}$  were calculated using equations (3) and (4). As mentioned above, the measurements with  $\alpha_i = \theta_i = 0^{\circ}$  were unusable, and so  $\theta_i$  and  $\alpha_i$  for equations (A.4) and (A.5), respectively, were held constant rather than 0. Table A.2 summarises the positions used for determining  $k_{1i}$  and  $k_{2i}$ . At each windspeed  $k_{1i}$  and  $k_{2i}$  were calculated, and the values taken as an average across windspeeds. Imaginary numbers were discarded.

	V(α)	from	V(0) from		change in $\alpha/\theta$	
k11	$\alpha_1 = 45^{\circ}$	$\theta_1 = 90^{\circ}$	$\alpha_1 = 0^{\circ}$	$\theta_1 = 90^{\circ}$	45°	
k <sub>12</sub>	$\alpha_2 = 45^{\circ}$	$\theta_2 = 90^{\circ}$	$\alpha_2 = 0^{\circ}$	$\theta_2 = 90^{\circ}$	45°	
k <sub>13</sub>	$\alpha_3 = 45^{\circ}$	$\theta_3 = 90^{\circ}$	$\alpha_3 = 0^{\circ}$	$\theta_3 = 90^{\circ}$	45°	
k <sub>21</sub>	$\alpha_1 = 45^{\circ}$	$\theta_1 = 90^{\circ}$	$\alpha_1 = 45^{\circ}$	$\theta_1 = 0^{\circ}$	90°	
k <sub>22</sub>	$\alpha_2 = 45^{\circ}$	$\theta_2 = 90^{\circ}$	$\alpha_2 = 45^{\circ}$	$\theta_2 = 0^{\circ}$	90°	
k <sub>23</sub>	$\alpha_3 = 45^{\circ}$	$\theta_3 = 90^{\circ}$	$\alpha_3 = 45^{\circ}$	$\theta_3 = 0^{o}$	90°	

Table A.2: Probe positions used for each k factor calculation.

The  $k_{1i}$  and  $k_{2i}$  thus determined were not final. They first were used in equation (2) with the corresponding wind speed vectors as determined from the pitot-manometer readings to calculate the effective cooling velocity for each wire.  $B_i$  and  $n_i$  were then solved using  $U_{eff}$  rather than U for each wire. The wind vectors for each wire were found using  $\alpha_i$  and  $\theta_i$  by

$$U_{x} = U \cos \alpha_{i} \cos \theta_{i}$$

$$U_{y} = U \sin \alpha_{i}$$

$$U_{z} = U \cos \alpha_{i} \sin \theta_{i}$$
(A.7)

Next  $k_{1i}$  and  $k_{2i}$  were recalculated with the new  $n_i$ , followed by  $B_i$  and  $n_i$  with the new  $k_{1i}$ and  $k_{2i}$ . All  $k_{1i}$ ,  $k_{2i}$ ,  $B_i$ , and  $n_i$  reached steady values with only two iterations.

To calculate the u-v-w wind components in wind tunnel co-ordinates from the raw voltage signals, U is calculated for each wire using equation (1). Then the velocity along each wire is calculated from equation (5). Multiplying these vectors by a co-ordinate transform matrix converts them from wire co-ordinates to wind tunnel co-ordinates. For the orthogonal triaxial probe the transform matrix is

Appendix A

	$\cos 45^\circ \cos 35.3^\circ$	cos 45° cos 35.3°	cos 54.7°	
ł	$-\cos 45^{\circ}$	cos 45°	0	<b>\</b> .
	– cos 45° sin 35.3°	- cos 45° sin 35.3°	cos 35.3°	

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