TURBULENCE IN AN ALMOND ORCHARD: SPATIAL VARIATIONS IN SPECTRA AND COHERENCE

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Abstract. The spatial variability of turbulence in a fully-leafed almond orchard was studied. Two three-dimensional sonic anemometers were used to measure turbulence spectra and coherence at different vertical and lateral separations inside the canopy. Peak frequencies of the horizontal velocity components, normalized by local horizontal wind speed, are greater in the canopy crown than in the trunkspace. Peak-normalized frequencies for the vertical velocity power spectra are similar in the canopy crown and in the subcanopy trunkspace. Spectral slopes in the inertial subrange are more negative than those predicted with Kolmogorov's $-\frac{2}{3}$ theory. It is thought that the foliage elements act to short-circuit the eddy cascade. Lateral separation of the instruments in the subcanopy trunkspace has little effect on the shape of the velocity spectra. On the other hand, lateral and vertical velocity coherences between spatially separated sensors are low inside the canopy. These low coherences are due to the Eulerian length scales being of the same order of magnitude as the separation distances of the anemometers. Phase angles between velocity components are about zero for small separation distances. When the two instruments are separated by 9 m and one instrument is positioned in a row while the other is between two rows, vertical velocities are about 180 deg out of phase and the streamwise velocities are about 40 to 60 deg out of phase. These data support the contention that preferred differences occur between within- and between-row wind flow regimes.

1. Introduction

Information regarding the scales of turbulence and their contribution to turbulent transfer above and within a vegetated canopy can be obtained by examining the power and cross spectra of wind velocity components. Properties of turbulence spectra measured in the surface boundary layer are relatively well known (e.g., Kaimal *et al.*, 1972; Anderson *et al.*, 1986). Power and cospectral densities are generally hump-shaped and scale with height (z), velocity (u), and natural frequency (n). Peak non-dimensional frequencies are on the order of 10^{-1} for the vertical velocity spectrum and 10^{-3} for the streamwise velocity and scalar power spectra (Raupach and Thom, 1981). At frequencies higher than the peak, spectral densities decrease into the inertial subrange in accordance with Kolmogorov's power law (see Jensen and Busch, 1982).

Turbulence spectra inside plant canopies differ from those measured in the surface layer. This is because different processes affect within-canopy turbulence. For example, turbulence in plant canopies results from mean shear and canopy element wake production and the resonant coupling between the canopy elements and the air flow, whereas above a plant canopy, turbulence is generated mainly by mean shear production (see Wilson and Shaw, 1977; Finnigan, 1979; Raupach and Thom, 1981). Turbulence spectra within plant canopies also do not seem to scale with any dimensionless frequency, unlike those above a canopy (Raupach and Thom, 1981; Finnigan, 1979).

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Peak frequencies in plant canopies also seem to be independent of height (Seginer *et al.*, 1976).

The body of literature reporting turbulence spectra measured inside plant canopies is relatively small since such measurements are difficult to make and sensor requirements are demanding. For reference, studies of turbulence in plant canopies are reported by Allen (1968), Shaw *et al.* (1974), Finnigan (1979) and Wilson *et al.* (1982). Studies conducted on model plant canopies in wind tunnels are reported in Seginer *et al.* (1976) and Raupach *et al.* (1986).

More studies of turbulence in plant canopies are, thus, needed to improve our understanding of within-canopy turbulent transfer processes. For example, little is known about the horizontal variability in canopy structure on wind flow and turbulence. Some evidence suggests that preferred differences occur between within-row and between-row wind flow regimes (Weiss and Allen, 1976; Baldocchi *et al.*, 1983). However, currently, many modelers spatially-average the horizontal wind field to simplify the system (e.g., Raupach and Shaw, 1981; Meyers and Paw U, 1986). We also know little about spatial variation in turbulence spectra or the influence of spatial separation on turbulence coherence in plant canopies. The only related work is the wind tunnel study of Seginer and Mulhearn (1978).

Turbulence spectra information can be used as a guide to improve the parameterization of higher order closure models. Other applications of within-canopy spectral data include improving our knowledge of: (a) dispersion and transfer of pollutants, spores and pollen in plant canopies; (b) the exchanges of CO_2, water vapor and heat, which affect plant growth; (c) canopy movement, as related to wind load on plants, which results in honami, lodging and windthrow; and (d) the dissipation of turbulence, as affected by plant parts.

Recently, we participated in a cooperative study (project Winds In Non-uniform Domains, WIND) conducted by the U.S. Forest Service and the U.S. Army Atmospheric Science Laboratory. Here we present turbulence spectra for the three wind velocity components observed in a uniform almond orchard. The influence of vertical and horizontal spatial separation on power spectra and the influence of spatial separation on the lateral and vertical coherence and on phase angles of the three velocity components are also examined.

2. Materials and Methods

2.1. Site, Canopy, and Ambient Conditions

Fluctuations in the three-dimensional wind velocity components were measured in a fully-leafed almond (*Prunus amygdalus*) orchard, located north of Chico, CA (lat. 39° N; long. 121° W). The experiment was conducted in April, 1986. The trees were about 8 m tall and had a leaf area index of about 1.3; leaf area was measured with the stratified clip-method. The mean profile of leaf area is presented in Figure 1. Leaf dimensions were on the order of about 0.04 to 0.06 m long and 0.02 m wide. The orchard

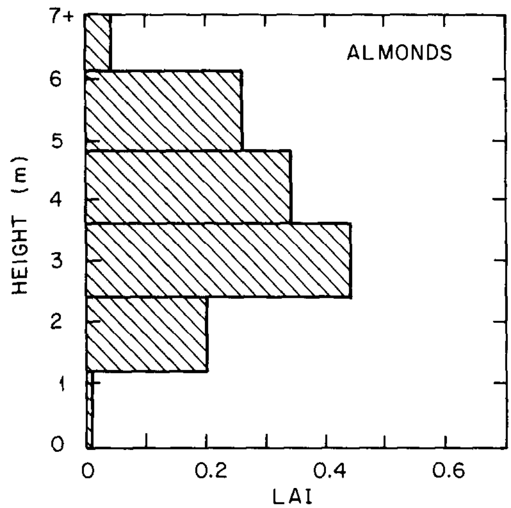

Fig. 1. Vertical profile of leaf area in the almond orchard.

was planted in a square pattern on approximately 8 m centers and was about 32 ha in size. Further details on the orchard and site are presented in Baldocchi and Hutchison (1987).

Wind directions during the experiment were generally between 135 and 155 degrees, providing a fetch of about 300 m. Wind speeds above the canopy (at 1.26 times canopy height) were moderate to brisk and net radiation levels were moderate to low; wind speeds typically ranged between 2.5 and 4.5 m s^{-1} and maximum net radiation values were less than 500 W m^{-2}, indicating near neutral to slightly unstable stability. Above canopy meteorological conditions are presented in Baldocchi and Hutchison (1987).

2.2. Instrumentation

Three-dimensional wind velocity components were measured with two sonic anemometers (Applied Technology Inc., Boulder, CO, model BH-478B/3). The resolution of the anemometers was about 0.0024 m s^{-1} and the zero offset was less than ± 0.10 m s^{-1}.

Three experiments were conducted using different spatial configurations of the anemometers. In the first experiment, the anemometers were separated vertically along a tower located at the midpoint between tree rows and columns. The anemometers were positioned at 0.51 times canopy height (h) and at $0.14h$; the upper anemometer was in the canopy crown, while the lower anemometer was in the subcanopy trunkspace. The sensor heads were extended about 3 m from the tower and were about 3.3 m in the lee of an upwind tree. In the second experiment, the anemometers were separated horizontally, with a lateral separation (across the mean wind direction) of about 3 m. Both instruments were positioned in the subcanopy trunkspace at $0.14h$ and measured within-row flow. The third experiment was similar to the second experiment, except that the instruments were separated laterally by 9 m and the second anemometer measured wind flow between two rows. During all three experiments the azimuthal orientation of the anemometers was adjusted so that mean wind flowed directly into the instruments, minimizing transducer shadowing effects.

The sonic anemometer signals were sampled and digitized at a rate of about 5 Hz with a computer-controlled data acquisition system. Data were stored on a magnetic hard-disk.

Wind speed components were measured above the canopy with a Gill uvw anemometer. These data were sampled with a micrologger data acquisition system (Campbell Scientific Instrument Company, Logan, UT, model CR-21X) at 1.2 Hz. More details on the instrumentation used in this experiment are reported in Baldocchi and Hutchison (1987).

2.2. Computational Procedures

Power and cross spectra and coherence were computed with the fast Fourier transform (FFT) technique using a program by Carter and Ferrie (1979). Computations were based on a time series of 4096 points. A one-dimensional coordinate rotation was performed on the wind data, making $\bar{v}$, the mean lateral velocity component, equal to zero. The FFT program tapered the time series at the ends to prevent 'leakage' and removed linear trends. The raw spectral densities were block-averaged to provide smoothed estimates over frequency bands. The spectral densities from several 14-min periods (16 to 20) were averaged to provide the data presented in this paper. This ensemble averaging increases the degrees of freedom and reduces the random noise and standard errors associated with spectra from individual periods.

3. Results and Discussion

3.1. Velocity Power Spectra

3.1.1. *Vertical Separation*

Figures 2a through 2c present power spectra for the vertical, streamwise, and lateral wind velocity components, respectively, for 0.51 and 0.14h. The spectral densities were multiplied by natural frequency (n) and were normalized by the variance. These normalized spectral values were plotted against wavenumber (the ratio between natural frequency (n) and local horizontal wind speed (u)). The turbulence statistics associated with these data are presented in Table I and are discussed in Baldocchi and Hutchison (1987).

The shape of these within-canopy power spectra resemble those measured in the surface boundary layer; the spectra are hump-shaped, with a prominent or broad peak. Others (e.g., Allen, 1968; Finnigan, 1979) have reported multiple peaks for within-canopy turbulence spectra from individual periods; such multiple peaks, however, may be an artifact of random noise associated with the computation of the spectral estimates.

TABLE I

Statistics of wind velocity components on D122 in an almond orchard. Vr is variance, Sk is skewness, and Kr is kurtosis.

Time (hr)	w — m s^{-1} —	u	Vr_w ——— (m s^{-1})^2 ———	Vr_u	Vr_v	Sk_w	Sk_u	Sk_v	Kr_w	Kr_u	Kr_v
Sonic anemometer #1, 0.51h											
9.0	0.08	0.64	0.23	0.39	0.79	-0.33	1.89	-1.15	5.68	6.25	3.42
9.5	0.06	0.80	0.29	0.72	1.15	-0.35	1.61	-1.24	5.66	3.71	2.89
10.0	0.08	0.73	0.31	0.57	1.08	-0.07	1.73	-1.20	5.09	4.43	3.04
10.5	0.12	0.65	0.27	0.40	0.76	-0.11	1.53	-1.26	5.62	4.33	3.55
11.0	0.12	0.64	0.25	0.35	0.72	-0.09	1.36	-1.54	4.42	4.03	4.03
11.5	0.10	0.58	0.28	0.35	0.68	-0.35	1.34	-1.69	6.28	4.05	5.51
12.0	0.09	0.62	0.25	0.34	0.77	-0.25	1.41	-1.47	5.19	4.03	3.80
13.0	0.11	0.55	0.23	0.29	0.63	-0.24	1.33	-1.52	5.41	4.96	5.34
13.5	0.09	0.56	0.26	0.28	0.64	-0.55	1.29	-1.75	6.57	4.39	5.29
14.0	0.10	0.57	0.27	0.34	0.49	-0.75	0.91	-1.33	7.33	4.65	5.84
AVG	0.10	0.63	0.26	0.40	0.77	-0.31	1.44	-1.42	5.72	4.48	4.27
SE	0.01	0.02	0.01	0.04	0.06	0.06	0.08	0.06	0.25	0.21	0.33
Sonic anemometer #2, 0.14h											
9.0	0.06	0.83	0.06	0.49	1.28	-0.02	1.46	-1.25	7.55	3.99	2.80
9.5	0.07	1.03	0.07	0.91	1.85	0.12	1.52	-1.22	6.58	3.75	2.36
10.0	0.08	0.93	0.07	0.65	1.70	0.09	1.49	-1.29	5.93	3.81	2.79
10.5	0.10	0.89	0.06	0.45	1.31	0.19	1.37	-1.00	5.42	4.31	2.57
11.0	0.09	1.02	0.07	0.49	1.10	-0.37	1.08	-0.95	7.15	4.64	3.04
11.5	0.09	0.86	0.06	0.40	1.07	0.13	1.01	-1.21	6.93	3.94	3.16
12.0	0.09	0.88	0.06	0.39	1.23	-0.56	1.22	-1.25	6.81	3.73	3.17
13.0	0.09	0.80	0.06	0.36	0.74	-0.11	0.75	-1.10	7.87	4.15	3.45
13.5	0.09	0.86	0.06	0.42	0.98	-0.11	0.75	-1.13	6.75	4.48	3.10
14.0	0.07	0.95	0.05	0.41	0.44	-0.12	0.59	-1.11	7.61	4.64	4.62
AVG	0.08	0.90	0.06	0.50	1.17	-0.08	1.12	-1.15	6.86	4.14	3.11
SE	0.00	0.02	0.00	0.05	0.13	0.07	0.10	0.03	0.23	0.11	0.19

The spectral peaks of the vertical velocity spectra (Figure 2a) occur at similar normalized frequencies (or wavenumbers) in the trunkspace and in the mid-canopy crown. If these power spectra were not normalized by wind speed, the spectral peak in the trunkspace would occur at a higher frequency than that in the canopy crown. A shift towards higher frequencies for the w power spectrum is expected as z approaches zero because the ground limits the size of the vertical eddies (Finnigan, 1979). Raupach and Shaw (1982) and Raupach *et al.* (1986) provide an alternative explanation. They state that peak frequencies of the w power spectrum shift towards higher frequencies as z/h decreases because large eddies, which predominantly transfer momentum to the canopy, progressively transfer their energy to smaller scales through the action of form drag by the foliage elements.

Spectral peaks for the streamwise (u) and lateral (v) velocity power spectra (Figures 2b and 2c) occur at higher normalized frequencies in the midcanopy crown than in the

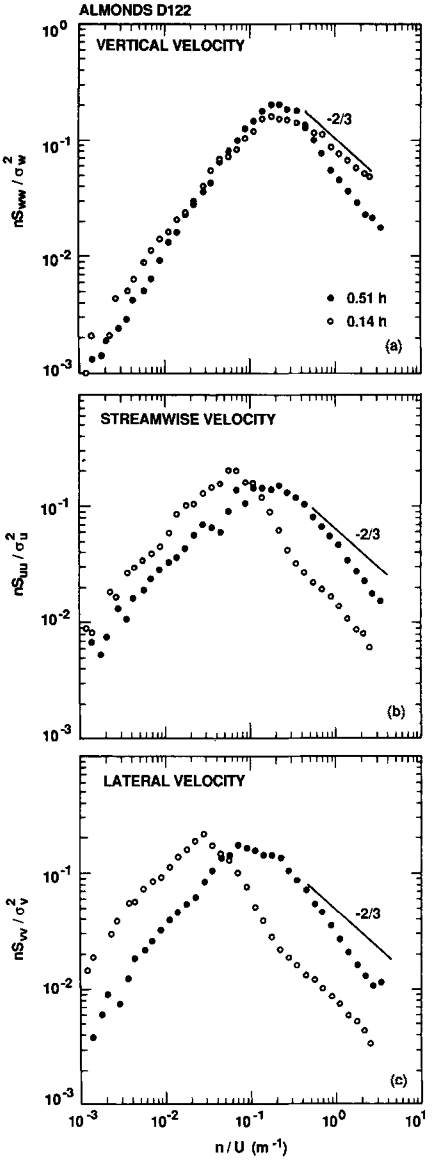

Fig. 2. Power spectra for the three velocity components at $0.51h$ and $0.14h$ for: (a) vertical velocity; (b) streamwise velocity; and (c) lateral velocity. These data are from day 122.

subcanopy trunkspace. This observation is the opposite of what is observed in the surface layer, where spectra scale according to nz/u. On the other hand, these results are in agreement with the measurements made in a larch plantation by Allen (1968). According to Allen (1968), peak frequencies of the horizontal wind speed spectrum shift toward lower frequencies in the trunkspace because most of the variation in wind speed is due to pressure waves associated with larger scale eddies; thus there is relatively little small scale turbulence in that region. On the other hand, the horizontal wind speed spectrum in the canopy crown is influenced by increased relative contributions from the smaller-scale eddies; the high plant area density in this region of the canopy generates small-scale turbulence and effectively breaks down large-scale eddies.

Allen's (1968) and our data should not be confused with the results of Raupach *et al.* (1986), who report that the u-spectrum shifts towards a higher peak frequency as z/h decreases. The measurements of Raupach *et al.* (1986) were made in an artificial canopy with a uniform vertical distribution of 'foliage' and a continuous well-developed flow. Thus, their canopy did not exhibit the feature of a trunkspace with little plant area density, as is observed in an almond orchard and a larch plantation. Any future attempt to scale turbulence spectra in a plant canopy should consider the vertical distribution of foliage, in addition to wind speed and the height above the ground.

At $0.14h$, peak normalized frequencies for the w, u, and v power spectra rank as: $w > u > v$. These peak values occur at about 0.2, 0.07, and 0.03 m^{-1}, respectively, for the w, u, and v power spectra. Peak values at $0.51h$ are less distinct ($w > = u > v$), but occur at about 0.25, 0.2, and 0.07 m^{-1}, respectively, for the w, u, and v power spectra. Assuming Taylor's hypothesis (the wavelength of the eddy is equal to u/n), peak normalized frequencies in the plant canopy are associated with eddies which have length scales on the order of 5 to 15 m.

The spectral peaks reported here are in broad agreement with values reported in the literature, accounting for different ways of normalizing spectral frequencies. Shaw *et al.* (1974) report that the spectral peak for u in a senescent corn canopy occurs at a normalized frequency ($f = nz/u$) of about 0.3. In wheat, Finnigan (1979) reports that the peak natural frequencies for the u and w power spectra occur at about 0.35 and 0.6 Hz, respectively. Allen (1968) reports lower spectral peaks for turbulence in a larch plantation; peak natural frequencies for horizontal wind speed occur between 0.04 and 0.10 Hz. A shift in the w power spectra, relative to the u and v spectra, has been observed by Wilson *et al.* (1982) in a corn canopy. Shaw *et al.* (1974), on the other hand, do not

TABLE II

Slopes of the velocity power spectra in the inertial subrange. Std. error is the standard error of the slope. These slopes were computed from linear regressions through the data in Figure 2 from a range of normalized frequencies between about 0.2 and 3 m^{-1}.

Spectra	Height	Slope	Std. error	r^2
$nS_{uu}/\overline{u'^2}$	$0.51h$	−0.951	0.0165	0.997
$nS_{uu}/\overline{u'^2}$	$0.14h$	−0.809	0.028	0.990
$nS_{vv}/\overline{v'^2}$	$0.51h$	−1.02	0.0140	0.998
$nS_{vv}/\overline{v'^2}$	$0.14h$	−0.704	0.0134	0.996
$nS_{ww}/\overline{w'^2}$	$0.51h$	−1.02	0.0372	0.988
$nS_{ww}/\overline{w'^2}$	$0.14h$	−0.630	0.0374	0.983

show a significant difference between the peak frequencies for the w and u power spectra.

At frequencies higher than the spectral peak, spectral densities decrease into the inertial subrange. In the atmospheric surface layer, spectral densities decrease with increasing frequency in the inertial subrange according to Kolmogorov's $-\frac{2}{3}$ power law (e.g., Kaimal *et al.*, 1972; Anderson *et al.*, 1986). Inside the almond orchard canopy, the slopes of the velocity spectra, at normalized frequencies exceeding 0.04 m^{-1}, range between -0.63 and -0.90 in the subcanopy and between -0.95 and -1.02 in the midcanopy crown (see Figure 2; Table II). The most negative spectral slopes are observed in the midcanopy crown, where the foliage density is greatest. Spectral slopes more negative than $-\frac{2}{3}$ suggest that the rate at which eddies cascade exceeds that predicted by Kolmogorov's scaling arguments. These greater rates in the eddy cascade of energy are probably due to plant elements breaking down the eddies, thus short-circuiting the eddy cascade, as suggested by Shaw and Seginer (1985). On the other hand, spectral slopes in the subcanopy trunkspace, where foliage is sparse, are in closer agreement with the slopes predicted by Kolmogorov's scaling theory.

Sensor noise cannot account for these large negative slopes in the inertial subrange, because sensor noise results in a slope of $+1$ (Wesely and Hart, 1985). Aliasing would also contribute to a more positive slope. However, aliasing was minimized by choosing an appropriate cutoff frequency for these spectra. A test of whether the observed slopes are significantly different from $-\frac{2}{3}$ is provided by examining the range of slopes of the power spectra in the inertial subrange, based on the standard errors associated with the spectral densities. A case is presented in Figure 3 for the u-power spectrum. These data show that the slopes of the u-power spectrum at $0.51h$ range between -0.84 and -1.07, while those at $0.14h$ range between -0.72 to -2.00. These slopes are, thus, significantly different from $-2/3$.

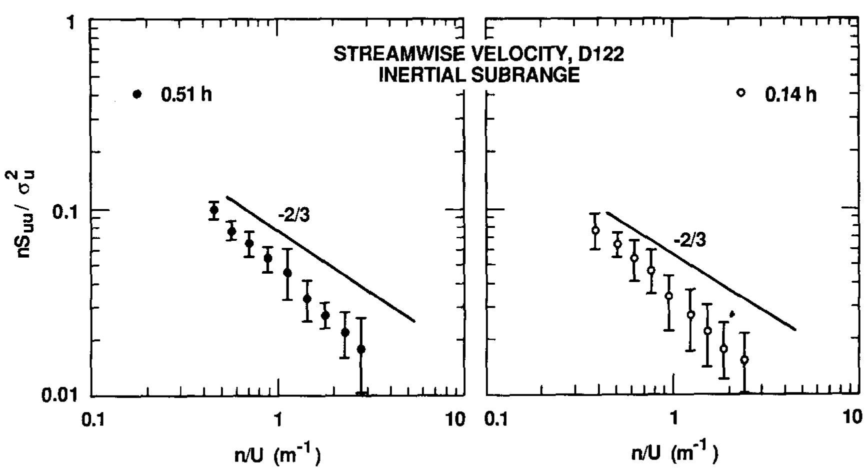

Fig. 3. Variations in the slope of the streamwise velocity power spectra based on plus/minus one standard error.

Wilson *et al.* (1982), Shaw *et al.* (1974), and Raupach *et al.* (1986) present within-canopy velocity spectra data that seem to follow Kolmogorov's scaling. Seginer *et al.* (1976), on the other hand, do not find a well-defined region where the spectral slope in the inertial subrange obeys the $-\frac{2}{3}$ power law. It is unclear at this point why some data in the literature follow the $-\frac{2}{3}$ power law, while other data do not. However, differences in canopy density seem to affect the 'short-circuiting' of the eddy cascade (see Shaw and Seginer, 1985). Tall forests and orchards may also influence the eddy cascade in a different manner than shorter crops. This is definitely a topic for further study.

Turbulence is isotropic if the ratios between the streamwise velocity (S_{uu}) and the lateral (S_{vv}) and vertical (S_{ww}) velocity spectral densities, S_{vv}/S_{uu} and S_{ww}/S_{uu}, equal $\frac{4}{3}$ in the inertial subrange (Jensen and Busch, 1982). Our data show that the ratios S_{vv}/S_{uu} at $0.51h$ and $0.14h$ are 1.27 ± 0.04 and 1.20 ± 0.04, respectively, suggesting some degree of isotropy between the horizontal components. On the other hand, the ratios S_{ww}/S_{uu} for $0.51h$ and $0.14h$ are 0.77 ± 0.03 and 0.64 ± 0.004, respectively, suggesting anisotropy between the horizontal and vertical turbulent components. Turbulence inside the canopy can, thus, be described as being axisymmetric, or 'squashed turbulence' (Kristensen *et al.*, 1983). Turbulence is axisymmetric in the atmospheric surface layer because the earth's surface 'squashes' the turbulence, by restricting vertical motions. As for the case presented here, interactions between canopy elements and the wind regime may also act to force the turbulent field towards anisotropy. Others report that both vertical and horizontal turbulence is anisotropic in plant canopies. Shaw *et al.* (1974) found that the ratios S_{ww}/S_{uu} and S_{vv}/S_{uu} in a corn canopy ranged between 0.90 and 0.94 and Seginer *et al.* (1976) found that these ratios in an artificial canopy equaled about one.

3.1.2. *Horizontal Separation*

The instruments were separated laterally in the subcanopy trunkspace to examine horizontal variability in the subcanopy wind field. Turbulence statistics for the second experiment, when the instruments were separated laterally by about 3 m, are presented in Table III and velocity spectra are presented in Figure 4. Essentially no differences are observed in the w, u, and v power spectra (Figures 4a, 4b, and 4c), at this small lateral separation.

Velocity spectra measured in a row and between two rows in the subcanopy for the w, u, and v components are presented in Figures 5a–5c, respectively. Here, the sensors were separated by about 9 m. The turbulence statistics associated with these data are presented in Table IV. Several features are to be noted in Table IV: mean horizontal and vertical wind velocities are greater for between-row flow than for within-row flow. The other turbulence statistics are in broad agreement. The power spectra show that there is generally little difference between the turbulence spectra measured in the row and between two rows. The only exception is that more energy is available at low normalized frequencies for the streamwise velocity component measured between two rows. Silver-

TABLE III

Statistics of wind velocity components on D120. Both anemometers were at 0.14h. The lateral separation distance between the instruments is about 3.1 m.

Time (hr)	w — m s^{-1} —	u	Vr_w —— (m s^{-1})^2 ——	Vr_u	Vr_v	Sk_w	Sk_u	Sk_v	Kr_w	Kr_u	Kr_v
Sonic anemometer #1, in the row											
1130	-0.03	0.53	0.05	0.35	0.44	-0.59	0.47	-0.39	5.54	3.50	2.76
1200	-0.05	0.44	0.06	0.27	0.67	-0.81	0.90	-0.88	6.57	3.70	2.39
1230	-0.03	0.62	0.05	0.50	0.94	-0.24	1.50	-1.35	5.14	3.19	2.63
1430	0.01	0.73	0.06	0.52	1.15	-0.30	1.44	-1.30	6.45	2.99	2.53
1500	0.01	0.82	0.06	0.79	1.28	-0.28	1.31	-1.45	5.66	2.83	2.76
1530	-0.00	0.69	0.05	0.68	1.04	-0.26	1.56	-1.42	6.81	3.38	2.63
1600	0.01	0.69	0.04	0.54	0.92	0.33	1.49	-1.24	8.34	2.98	2.25
1630	-0.00	0.73	0.05	0.44	1.10	-0.34	1.37	-1.26	6.80	3.48	2.60
1700	0.00	0.77	0.05	0.68	1.10	-0.14	1.51	-1.43	6.28	3.19	2.74
AVG	-0.01	0.67	0.05	0.53	0.96	-0.29	1.28	-1.19	6.40	3.25	2.59
SE	0.01	0.04	0.00	0.05	0.08	0.10	0.11	0.11	0.29	0.09	0.06
Sonic anemometer #2. Separated laterally 3.1 m from anemometer #1											
1130	0.02	0.63	0.04	0.34	0.37	-0.39	0.43	-0.69	6.14	3.21	3.06
1200	0.02	0.51	0.04	0.30	0.48	-0.34	0.88	-0.96	5.76	4.04	2.66
1230	0.02	0.62	0.04	0.32	0.84	-0.19	1.29	-1.22	5.81	3.24	2.43
1430	0.02	0.77	0.06	0.36	0.99	-0.06	1.22	-1.19	5.88	3.33	2.46
1500	0.02	0.83	0.06	0.53	1.19	-0.80	1.08	-1.41	8.27	3.11	2.87
1530	0.03	0.66	0.04	0.36	0.95	-0.00	1.41	-1.33	9.81	3.43	2.85
1600	0.03	0.68	0.04	0.32	0.77	-0.24	1.22	-1.16	7.28	3.44	2.42
1630	0.01	0.79	0.05	0.36	0.95	-0.81	1.11	-1.20	10.45	4.71	2.48
1700	0.02	0.75	0.05	0.38	0.95	-1.09	1.27	-1.34	16.00	3.40	2.65
AVG	0.02	0.69	0.05	0.36	0.83	-0.44	1.10	-1.17	8.49	3.55	2.65
SE	0.00	0.03	0.00	0.02	0.08	0.12	0.09	0.07	1.03	0.16	0.07

sides (1974) also shows little horizontal variability in temperature spectra measured in a row of corn and between two rows.

3.2. Velocity cospectra

The cospectrum for the uw covariance measured at 0.51h is presented in Figure 6. The peak normalized frequency is about 0.07 m^{-1}, which is in general agreement with data based on natural frequency from Shaw *et al.* (1974). These peak values, on the other hand, are a decade lower than the natural frequency values reported by Finnigan (1979) for wheat. In the inertial subrange, the slope of the cospectrum is approximately $-\frac{4}{3}$, which is in relative agreement with Kolmogorov's theory (e.g., Busch and Jensen, 1982). The uw cospectrum measured at 0.14h is not presented since little tangential momentum stress was present at that level.

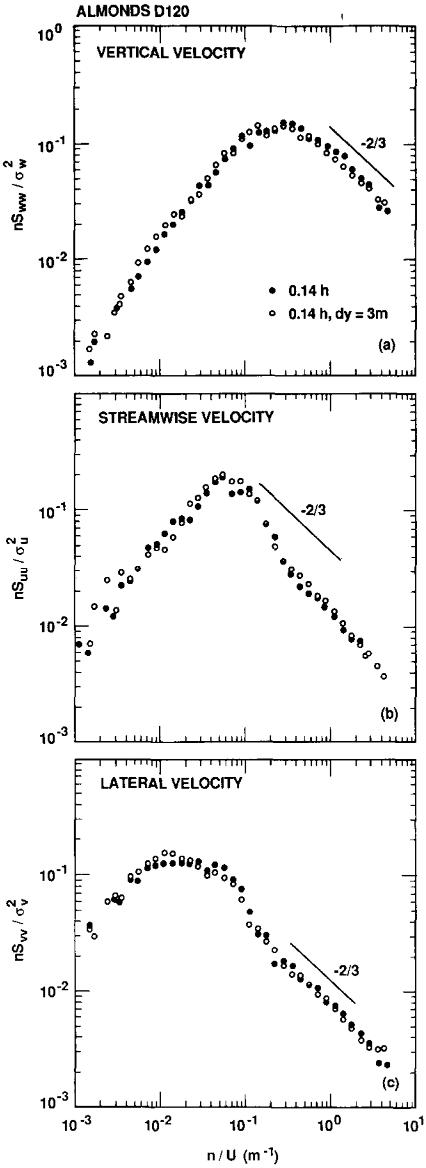

Fig. 4. Power spectra for the three velocity components at $0.14h$ and separated laterally by 3.1 m for: (a) vertical velocity; (b) streamwise velocity; and (c) lateral velocity. These data are from day 120.

3.3. Velocity coherence

Another way of investigating the spatial and temporal behavior of turbulence is by examining the coherence of the velocity components measured at two points. Theories and measurements of turbulence coherence in the atmospheric boundary layer are well established in the literature (e.g., Davenport, 1961; Kristensen and Jensen, 1979;

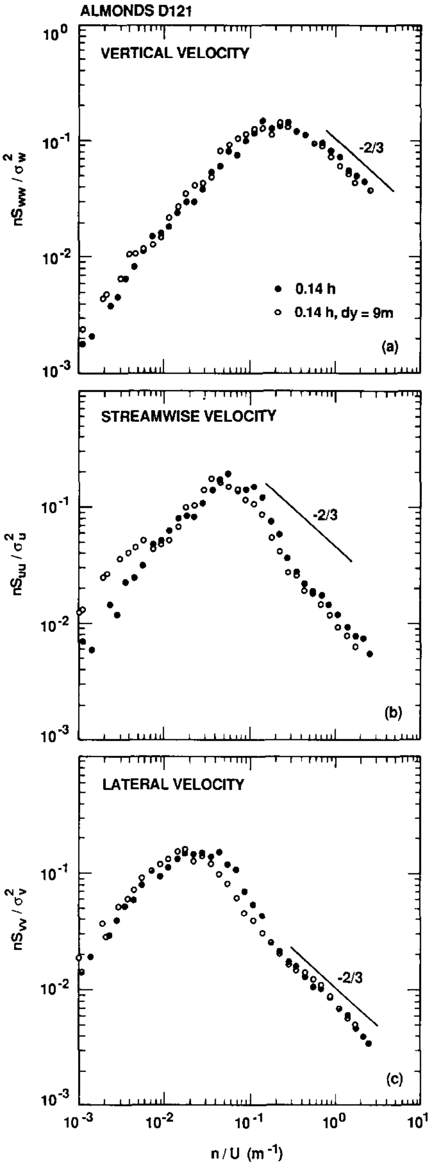

Fig. 5. Power spectra for the three velocity components at $0.14h$ and separated laterally by 9 m for: (a) vertical velocity; (b) streamwise velocity; and (c) lateral velocity. These data are from day 121.

Kristensen *et al.*, 1981). On the other hand, to our knowledge, no measurements of velocity coherence are available from within plant canopies; the only related study is that of Seginer and Mulhearn (1978), who report vertical coherence measurements made inside a model plant canopy.

Coherence is defined as:

$$\mathrm{coh}(n, d, i, j) = \frac{\mathrm{Co}(n)^2 + Q(n)^2}{S_1(n)S_2(n)} \tag{1}$$

TABLE IV

Statistics of wind velocity components on D121 in an almond orchard. The lateral separation distance between two anemometers is 9 m. Vr is variance, Sk is skewness, and Kr is kurtosis.

Time (hr)	w — m s^{-1} —	u	Vr_w —— (m s^{-1})^2 ——	Vr_u	Vr_v	Sk_w	Sk_u	Sk_v	Kr_w	Kr_u	Kr_v
Sonic anemometer #1, 0.14h, in the row											
1000	0.05	0.86	0.06	0.45	0.95	0.22	0.83	-1.09	5.42	3.56	2.58
1030	0.06	0.97	0.08	0.66	1.68	0.16	1.41	-1.26	6.02	3.24	2.48
1100	0.04	0.79	0.05	0.41	1.08	-0.34	1.22	-1.12	7.50	3.83	2.42
1200	0.06	0.82	0.07	0.51	1.15	-0.21	1.25	-1.36	8.95	2.91	2.62
1300	0.06	0.94	0.09	0.69	1.64	-0.31	1.34	-1.24	6.70	3.01	2.61
1400	0.06	0.88	0.07	0.57	1.49	0.10	1.45	-1.33	4.75	3.58	2.65
1430	0.05	1.07	0.09	1.20	1.98	-0.47	1.52	-1.35	5.16	2.97	2.33
1500	0.05	1.06	0.08	1.11	1.81	0.08	1.52	-1.36	7.44	3.08	2.55
AVG	0.05	0.92	0.07	0.70	1.47	-0.10	1.32	-1.26	6.49	3.27	2.53
SE	0.01	0.10	0.01	0.28	0.35	0.25	0.21	0.10	1.33	0.32	0.10
Sonic anemometer #2, 0.14h, between rows											
1000	0.08	1.12	0.07	0.50	0.87	-0.42	0.85	-1.45	7.60	3.95	2.73
1030	0.10	1.17	0.09	0.65	1.35	-0.55	1.09	-1.41	8.18	3.19	2.92
1100	0.09	1.07	0.06	0.48	0.86	-0.97	1.09	-1.41	8.80	4.63	2.93
1200	0.10	1.13	0.08	0.55	1.09	-0.54	0.90	-1.53	9.31	3.57	2.91
1300	0.12	1.22	0.10	0.63	1.41	-0.47	0.89	-1.41	7.50	3.37	2.85
1400	0.10	1.11	0.08	0.59	1.24	-0.53	1.18	-1.44	7.05	3.70	2.84
1430	0.14	1.20	0.10	0.80	1.95	-0.41	1.37	-1.21	10.96	3.58	2.84
1500	0.12	1.19	0.08	0.64	1.50	-0.59	1.43	-1.47	7.65	4.04	2.78
AVG	0.11	1.15	0.08	0.60	1.28	-0.56	1.10	-1.42	8.38	3.75	2.85
SE	0.02	0.05	0.01	0.09	0.34	0.17	0.20	0.09	1.19	0.42	0.07

where i is the velocity component index (1, 2, and 3 stand for u, v, and w, respectively), j is the spatial orientation index (1, 2, and 3 stand for x, y, and z), d is the separation distance, Co is the cospectrum density, Q is the quadrature spectrum density and S_1 and S_2 are the spectral densities of the power spectra for the velocity component of interest at locations 1 and 2. Lateral coherence is defined for sensors separated in the y-direction; this orientation is perpendicular to the wind, which is incoming from the x-direction. Vertical coherence is defined for sensors separated in the z-direction.

In the surface layer, if the separation distance is much smaller than the integral length scale of the turbulence, coherence values approach unity as the separation distance approaches zero and they approach zero when separation distances are much greater than the typical scale lengths of the turbulence (Kristensen and Jensen, 1979; Jensen and Busch, 1982). Davenport (1961) reports that coherence values decrease logarithmically with linear increases in n.

Coherence values for vertical, streamwise and lateral velocity components are presented in Figure 7 as a function of natural frequency, n. Several features are observed

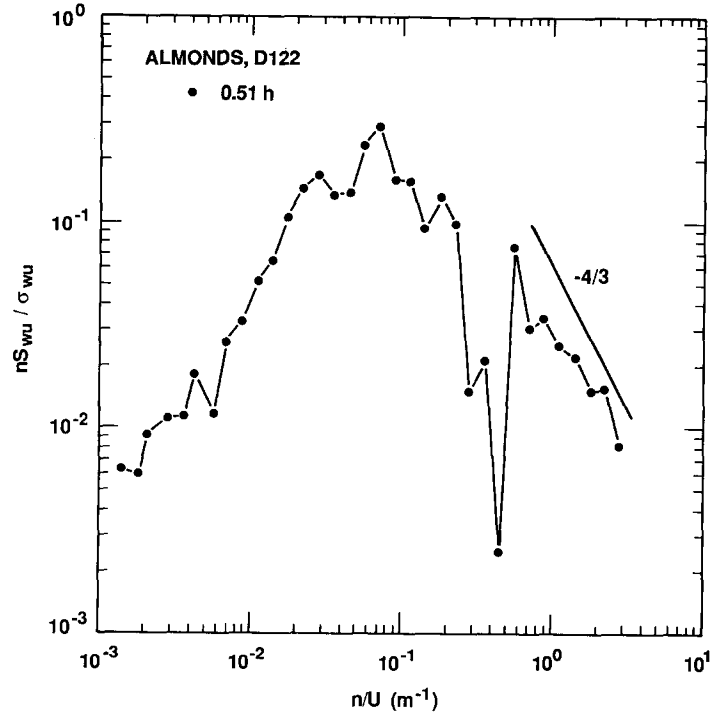

Fig. 6. *uw* cospectrum for 0.51*h*. These data are from day 122.

in these data. First, under low frequencies ($n < 0.01$ Hz), coherence values rank as $v > u > = w$. This ranking is in agreement with the theoretical predictions of Kristensen and Jensen (1979), for conditions when differences between the separation distance and the Eulerian integral length scale of the turbulence (L) are small. The maximum coherence values, at low frequencies and varying separation distances, range between 0.6 and 1.0 for v, 0.2 and 0.9 for u, and 0.1 and 0.3 for w. These values are much lower than those commonly observed in the surface layer, where commonly $d \ll L$. On the other hand, these results compare reasonably with data taken under conditions of $d \sim L$ (Kristensen and Jensen, 1979).

Coherence values deviating from unity at low frequencies probably occur in a plant canopy since separation distances are of the same order as L. This is because the foliage breaks down the eddies, reducing L with depth into the canopy (Allen, 1968; Wilson *et al.*, 1982); typical Eulerian length scales in the subcanopy of a 10 m tall forest are on the order of 2 m (Allen, 1968).

Secondly, lateral coherence values for the u, w, and v components decrease as the lateral separation in y increases. This observation agrees with conceptual properties of coherence. Values of vertical coherence (for horizontal velocity components) are smaller than those of lateral coherence at similar separation distances. This phenomenon is also observed in measurements made in the atmospheric surface layer.

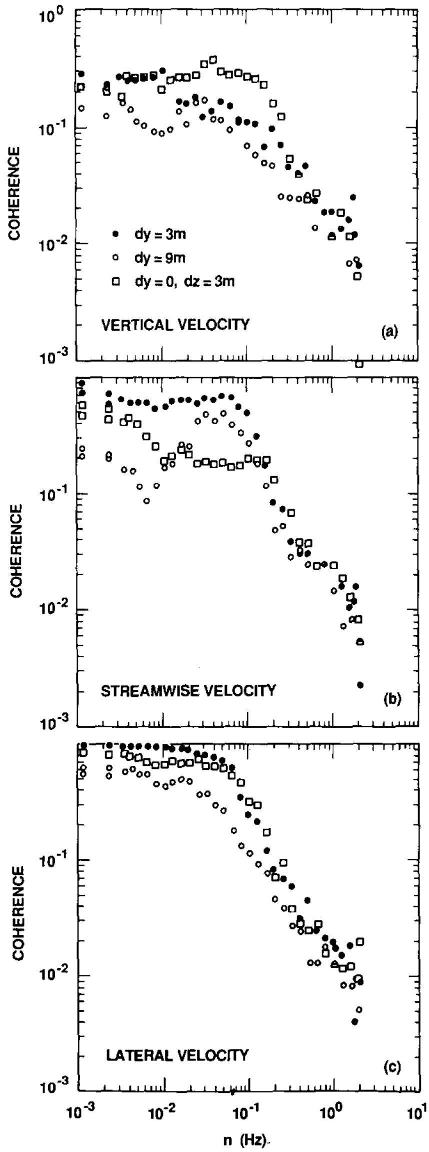

Fig. 7. Lateral and vertical coherence for the three velocity components: (a) vertical velocity; (b) streamwise velocity and; (c) lateral velocity. Data are presented for lateral separations (dy) of 3 and 9 m and for vertial separations (dz) of 3 m.

Thirdly, coherence values, plotted on a log-log scale, are relatively constant at low frequencies and collapse to zero at frequencies greater than 0.1 Hz. More often, coherences are presented on a log-linear scale and decrease exponentially with increasing n (Davenport, 1961; Panofsky, 1973; Seginer and Mulhearn, 1978). Exponential functions fit to the coherence data in Figure 7 show that the extinction coefficients for the u, v, and w coherences range between -3 and -8 (Table V). These

TABLE V

Regression coefficients for the relationship: $\mathrm{Coh}(n) = a \exp(bn)$

	a	b	r^2
u, $dy = 3$ m	0.59	−4.78	0.86
u, $dy = 9$ m	0.28	−4.70	0.62
u, $dz = 3$ m	0.32	−3.96	0.81
v, $dy = 3$ m	0.72	−5.04	0.83
v, $dy = 9$ m	0.47	−7.32	0.87
v, $dz = 3$ m	0.70	−5.92	0.89
w, $dy = 3$ m	0.20	−3.02	0.87
w, $dy = 9$ m	0.17	−4.18	0.81
w, $dz = 3$ m	0.27	−3.63	0.86

values are much smaller than those in the atmospheric boundary layer, where the natural frequency is normalized by separation distance and wind speed (Davenport, 1961); we cannot claim this to be a proper scaling factor within a canopy because the foliage distribution affects the coherence values.

In the atmospheric boundary layer, extinction coefficients of u for vertical coherence are on the order of 30 (Panofsky, 1973), while those for lateral coherence are on the order of 11 (Kristensen and Jensen, 1979). Proper scaling of frequency-coherence relationships in plant canopies may need to rely on an index based on some factor such as canopy density.

Phase angles provide additional information for the interpretation of spectral coherence. Phase angle is defined as:

$$\phi(n, d, i, j) = \arctan(Q(n)/\mathrm{Co}(n)) . \tag{2}$$

It represents the relative contribution of the quadrature spectrum and the cospectrum components to the cross-spectrum in the real and imaginary planes.

Figure 8 presents phase angles for the vertical, streamwise and lateral velocity components for vertical and lateral separations. For vertical and lateral separations of 3 m, phase angles are near zero (on the order of ± 20 deg, at frequencies less than 0.1 Hz). When the lateral separation is 9 m, the phase angles for the vertical velocity component, at low frequencies, are on the order of ± 60 to 180 deg, while those for streamwise velocity are on the order of ± 40 to 60 deg.

The 180 deg phase shift in vertical velocities, separated by 9 m, indicates that when vertical velocities, in the row, are directed upward, vertical velocities, between the rows, are directed downward, and *vice versa*. The −40 to −60 deg phase angle shift in streamwise velocity, for the 9 m lateral separation, suggests that as a large horizontal wind gust sweeps through the subcanopy, the streamwise wind velocity in the row is retarded and the gust is delayed in comparison to that between the row. This retardation is expected due to the differences in horizontal wind speed (Table IV).

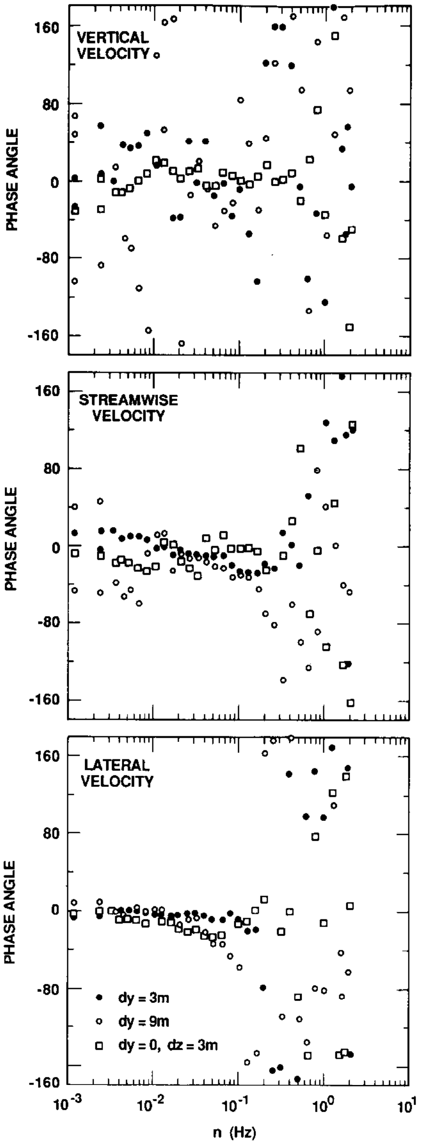

Fig. 8. Lateral and vertical phase angles for the three velocity components: (a) vertical velocity; (b) streamwise velocity and; (c) lateral velocity. Data are presented for lateral separations (dy) of 3 and 9 m and for vertical separations (dz) of 3 m.

These results support those of Weiss and Allen (1976), who reported that the circulation pattern of turbulence between rows in a vineyard can be represented by intermittent eddies rather than standing vortices, as hypothesized by Perrier *et al.* (1972).

4. Summary

Peak frequencies, normalized by local wind speed, for the horizontal velocity power spectra are greater in the mid-canopy crown than in the subcanopy trunkspace, an observation in agreement with the data of Allen (1968). On the other hand, the peak normalized frequencies of the vertical velocity power spectra are similar in the canopy crown and the subcanopy trunkspace. Spectral slopes in the inertial subrange are more negative than values predicted with Kolmogorov's $-\frac{2}{3}$ power law. These greater slopes may be an artifact of the foliage acting to short-circuit the eddy cascade. The spectral data also suggest that turbulence inside the almond canopy is anisotropic.

Lateral separation of the instruments in the subcanopy had little effect on the shape of the velocity spectra. An examination of the spectral coherence and phase angles, however, provided an alternative means of studying the influence of spatial separation on within-canopy turbulence. Spectral coherence values of velocity components are less than one, for low frequencies and at separation distances on the order of the canopy height. Low coherence values are due to the Eulerian length scales being of the same order of magnitude as the separation distances. The magnitudes of coherence values at low frequencies rank as $v > u > = w$.

The examination of phase angles helps to develop a simple picture of the intermittent circulation of the large eddies in the canopy. When the sensors were separated by 9 m, with one instrument in the row and the other between two rows, vertical velocities were about 180 deg out of phase. Horizontal wind speeds in the row lag those between two rows by about 40 to 60 deg because the trees retard the within-row wind flow. These data suggest that preferred differences occur between within- and between-row wind flow regimes.

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References

Allen, L. H., Jr.: 1968, 'Turbulence and Wind Speed Spectra within a Japanese Larch Plantation', *J. Appl. Meteorol.* **7**, 73–78.

Anderson, D. E., Verma, S. B., Clement, R. J., Baldocchi, D. D., and Matt, D. R.: 1986, 'Turbulence Spectra of CO_2, Water Vapor, Temperature and Velocity over a Deciduous Forest', *Agric. For. Meteorol.* **38**, 81–99.

Baldocchi, D. D., Verma, S. B., and Rosenberg, N. J.: 1983, 'Characteristics of Air Flow Above and Within Soybean Canopies', *Boundary-Layer Meteorol.* **25**, 43–54.

Baldocchi, D. D. and Hutchison, B. A.: 1987, 'Turbulence in an Almond Orchard: Vertical Variations in Turbulent Statistics', *Boundary-Layer Meteorol.* **40**, 127–146.

Carter, G. C. and Ferrie, J. F.: 1979, 'A Cohrence and Cross Spectral Estimation Program', *Programs for Digital Signal Processing*, Digital Processing Committee, (eds.), IEEE press, pp. 2.3–1 to 2.3–18.

Davenport, A. G.: 1961, 'The Spectrum of Horizontal Gustiness Near the Ground in High Winds', *Quart. J. Roy. Meteorol. Soc.* **87**, 194–211.

Finnigan, J. J.: 1979, 'Turbulence in Waving Wheat. I: Mean Statistics and Honami', *Boundary-Layer Meteorol.* **16**, 181–212.

Jensen, N. O. and Busch, N. E.: 1982, 'Atmospheric Turbulence', in E. J. Plate (ed.), *Engineering Meteorol.* Elsevier Sci. Publ., pp. 179–231.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., Cote, O. R.: 1972, 'Spectral Characteristics of Surface Layer Turbulence, *Quart. J. Roy. Meteorol. Soc.* **98**, 563–589.

Kristensen, L. and Jensen, N. O.: 1979, 'Lateral Coherence in Isotropic Turbulence and in the Natural Wind', *Boundary-Layer Meteorol.* **17**, 353–373.

Kristensen, L., Kirkegaard, P., and Lenschow, D. H.: 1983, *Squashed Atmospheric Turbulence*, Riso National Laboratory, Denmark, *Riso-R-478*, 79 pp.

Kristensen, L., Panofsky, H. A., Smith, S. D.: 1981, 'Lateral Coherence of Longitudinal Wind Components in Strong Winds', *Boundary-Layer Meteorol.* **21**, 199–205.

Meyers, T. P. and K. T., Paw U: 1986, 'Testing of a Higher Order Closure Model for Modeling Airflow Within and Above Plant Canopies', *Boundary-Layer Meteorol.* **37**, 297–311.

Panofsky, H. A.: 1973, 'Tower Meteorology', in D. A. Haugen (ed.), *Workshop on Micrometeorol.* Amer. Meteorol. Soc., Boston, MA, pp. 151–174.

Perrier, E. R., Robertson, J. M., Millington, R. J., and Peters, D. B.: 1972, 'Spatial and Temporal Variation of Wind Above and Within a Soybean Canopy', *Agric. Meteorol.* **10**, 421–442.

Raupach, M. R. and Shaw, R. H.: 1982, 'Averaging Procedures for Flow Within Vegetation Canopies', *Boundary-Layer Meteorol.* **22**, 79–90.

Raupach, M. R. and Thom, A. S.: 1981, 'Turbulence In and Above Plant Canopies, *Ann. Rev. Fluid Mech.* **13**, 97–129.

Raupach, M. R., Coppin, P. A., and Legg, B. J.: 1986, 'Experiments on Scalar Dispersion Within a Model Plant Canopy, Part 1: The Turbulent Structure', *Boundary-Layer Meteorol.* **35**, 21–52.

Seginer, I., Mulhearn, P. J., Bradley, E. F., and Finnigan, J. J.: 1976, 'Turbulent Flow in a Model Plant Canopy', *Boundary-Layer Meteorol.* **10**, 423–453.

Seginer, I. and Mulhearn, P. J.: 1978, 'A Note on Vertical Coherence of Streamwise Turbulence Inside and Above a Model Plant Canopy', *Boundary-Layer Meteorol.* **14**, 515–523.

Shaw, R. H., Silversides, R. H., and Thurtell, G. M.: 1974, 'Some Observations of Turbulence and Turbulent Transport Within and Above Plant Canopies', *Boundary-Layer Meteorol.* **5**, 429–449.

Shaw, R. H. and Seginer, I.: 1985, *The Dissipation of Turbulence in Plant Canopies, 7th Symposium on Turbulence and Diffusion*, American Meteorol. Soc., Boston, MA, pp. 200–203.

Silversides, R. H.: 1974, 'On Scaling Parameters for Turbulence Spectra Within Plant Canopies', *Agric. Meteorol.* **13**, 203–211.

Weiss, A., and Allen, L. H., Jr.: 1976, 'Air Flow Patterns in Vineyard Rows', *Agric. Meteorol.* **16**, 329–342.

Wesely, M. L. and Hart, R. L.: 1985, 'Variability of Short Term Eddy Correlation Estimates of Mass Exchange', in B. A. Hutchison and B. B. Hicks (eds.), *Forrest-Atmosphere Interactions*, D. Reidel Publ. Co., Dordrecht, Holland, pp. 591–612.

Wilson, N. R. and Shaw, R. H.: 1977, 'A Higher Order Closure Model for Canopy Flow', *J. Appl. Meteorol.* **16**, 1197–1205.

Wilson, J. D., Ward, D. P., Thurtell, G. W., and Kidd, G. E.: 1982, 'Statistics of Atmospheric Turbulence Within and Above a Corn Canopy', *Boundary-Layer Meteorol.* **24**, 495–519.