TURBULENCE STRUCTURE IN A DECIDUOUS FOREST

DENNIS D. BALDOCCHI and TILDEN P. MEYERS

Atmospheric Turbulence and Diffusion Division/NOAA/ARL, P.O. Box 2546, Oak Ridge, TN 37831, U.S.A.

(Received in final form 23 November, 1987)

Abstract. Three-dimensional wind velocity components were measured at two levels above and at six levels within a fully-leafed deciduous forest. Greatest shear occurs in the upper 20% of the canopy, where over 70% of the foliage is concentrated. The turbulence structure inside the canopy is characterized as non-Gaussian, intermittant and highly turbulent. This feature is supported by large turbulence intensities, skewness and kurtosis values and by the large infrequent sweeps and ejections that dominate tangential momentum transfer. Considerable day/night differences were observed in the vertical profiles of the mean streamwise wind velocity and turbulence intensities since the stability of the nocturnal boundary layer dampens turbulence above and within the canopy.

1. Introduction

In the past decade, many theoretical advances have been made, regarding the description of turbulence transfer in plant canopies, using higher-order closure and Lagrangian models (e.g., Shaw, 1976; Wilson and Shaw, 1977; Wilson *et al.*, 1981; Raupach and Shaw, 1982; Finnigan, 1985; Meyers and Paw U, 1986; Raupach, 1987). Unfortunately, little of the available within-canopy wind data is adequate to test and improve these models since much of these data consists only of measurements of mean scalar wind speed (e.g., Landsberg and James, 1971; Kalma and Stanhill, 1972). Studies by Shaw *et al.* (1974a, b), Finnigan (1979a, b), Wilson *et al.* (1982) and Baldocchi and Hutchison (1987, 1988) provide examples of the few detailed turbulence measurements in plant canopies that are available in the literature. Excellent wind tunnel studies by Seginer *et al.* (1976) and Raupach *et al.* (1986) provide additional information on turbulence structure in artificial plant canopies, but these studies are limited by the inability to build realistic physical models of the plant canopy and to simulate intermittent events.

Additional measurements of wind velocity components and their higher order statistical moments are needed in different plant canopy structures to test and improve the parameterizations to higher-order closure and Lagrangian models. Currently, there are some discrepancies between model assumptions and conditions measured in the field that need to be resolved. For example, some higher order closure models assume a quasi-Gaussian approximation to model the fourth moments in the third-order budget equations (e.g., Shaw and Seginer, 1987. Meyers and Paw U, 1986). On the other hand, field measurements suggest that the quasi-Gaussian approximation is questionable because turbulence in the canopy is highly skewed, kurtotic and intermittent (Shaw and Seginer, 1987; Raupach *et al.*, 1986; Baldocchi and Hutchison, 1987). The dissipation of turbulence, in higher-order closure models, is commonly parameterized with length scales, derived from surface boundary-layer arguments. Yet, some field data suggest that

Boundary-Layer Meteorology **43** (1988) 345–364.

plant elements act to short-circuit the normal eddy cascade process, which may alter the dissipation rate of turbulence (Shaw and Seginer, 1985; Baldocchi and Hutchison, 1988), whereas other field data show that the eddy cascade proceeds according to Kolmogorov's scaling arguments (e.g., Wilson *et al.*, 1982; Shaw *et al.*, 1974b). Some Lagrangian models assume a homogeneous turbulence field inside the canopy (Raupach, 1987), yet field and wind tunnel measurements indicate that turbulence is actually inhomogeneous inside plant canopies (Wilson *et al.*, 1982; Raupach *et al.*, 1986). Other Lagrangian models account for inhomogeneous turbulence (Wilson *et al.*, 1981; Legg and Raupach, 1982). However, information on the vertical profiles of Lagrangian time-scales and velocity statistics is required and further testing of these models is needed.

The turbulence studies, referenced above, deal only with measurements in uniform agricultural crops. Additional information regarding turbulence in heterogeneous forest canopies is also needed to improve our understanding of the influence of different canopy architectures on turbulence structure. Numerical experiments by Shaw and Pereira (1982) suggest that stability effects may be significant in tall canopies. They also demonstrate that canopies with different roughnesses and leaf area distributions greatly influence such factors as the mean level of momentum absorption by the canopy (the zero-plane displacement height).

The objectives of this study are to present and examine the vertical variation of turbulence statistics and the intermittency of turbulence inside a fully-leafed deciduous forest. Details on spectra and turbulent length scales are presented in a companion paper (Baldocchi and Meyers, 1988).

2. Materials and Methods

2.1. Site and Canopy Structure

Three-dimensional wind velocity components were measured in a deciduous forest during September and October, 1986, when the canopy was fully-leafed. The experimental site is located at the Atmospheric Turbulence and Diffusion Division's Forest Meteorology research site, on the U.S. Department of Energy's Reservation near Oak Ridge, TN (lat. 35°57′30″ N; long. 84°17′15″ W; 365 m above m.s.l.). This site is situated on a ridge in moderately sloping terrain. A topographic map of the site is presented in Verma *et al.* (1986). The vegetation at the site consists of an uneven-aged, mixed species stand of predominantly oak and hickory trees (*Quercus* and *Carya* spp.). The average height (h) of the stand is about 23 m.

The leaf area and silhouette woody biomass index are about 4.9 and 0.6, respectively, under fully-leafed conditions. A vertical profile of the leaf area index of the canopy is presented in Figure 1. Species and architectural characteristics of the stand are described in Hutchison *et al.* (1986). The deciduous forest extends for several kilometers in all directions except with intermittent inclusions of loblolly pine (*Pinus taeda*).

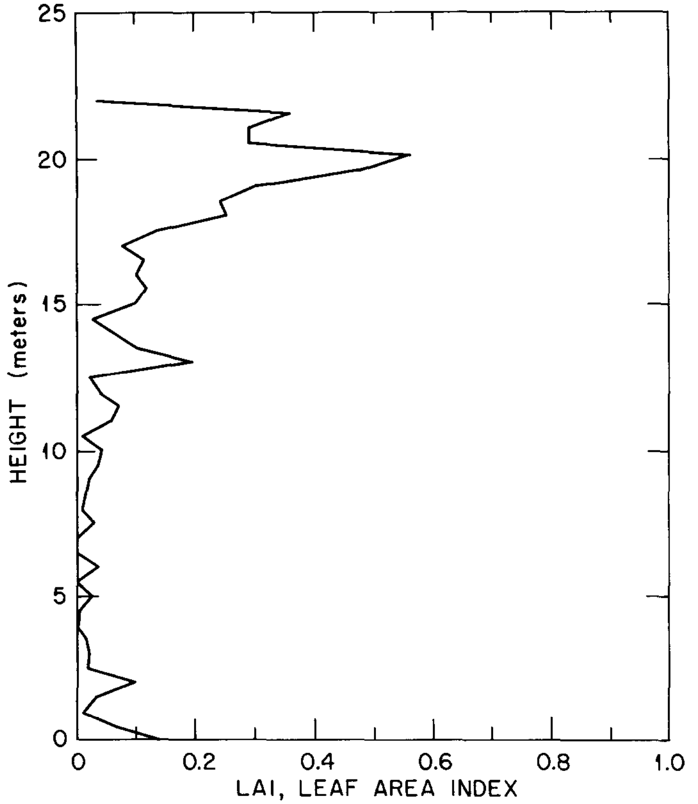

Fig. 1. Vertical variation in leaf area index in a deciduous forest canopy.

2.2. Instrumentation

Three-dimensional, wind velocity components were measured within the canopy with three sonic anemometers (Applied Technology Inc. Boulder, CO, model BH-478B/3). The resolution of the anemometers is about 0.0024 m s^{-1} and the zero offset is less than $\pm$ 0.10 m s^{-1}. A Gill uvw propeller anemometer was used to measure wind velocity components above the canopy. The propeller anemometers were fitted with extension shafts, as recommended by Hicks (1972). Temperature fluctuations were measured above the canopy with a microbead thermistor to determine sensible heat flux.

The sonic anemometers were supported on swivel-booms, that were attached to a 33 m tall triangular tower. Access to the instruments was provided by an adjacent 44 m tall walk-up tower. The azimuthal angle of the anemometer booms was oriented so that the wind generally flowed into the sensor heads, minimizing 'transducer-shadowing effects' (Wyngaard and Zhang, 1985). The sensor heads extended about 3 m upwind of the tower, thus minimizing 'tower-shadowing' effects.

We were unable to measure wind simultaneously at all desired heights. Consequently,

TABLE I

Levels of instrument placement and number n of half-hour periods used in the analysis of profiles of turbulence structure parameters. H is canopy height.

Height (z)	z/H	n (day)	n (night)
34	1.45	74	116
24	1.02	35	37
22	0.94	13	12
20.7	0.88	9	10
18	0.77	47	59
10	0.46	13	29
6.9	0.29	14	–
2.6	0.11	31	39

several experiments were conducted with different instrument configurations. Table I presents the measurement levels and the number of periods used to construct the averages presented in this paper. Wind velocity was measured above the canopy, at 34 m, during each experiment.

The transducer signals were sampled and digitized at a rate of 7.6 Hz with a computer-controlled data acquisition system. Instantaneous data were written to a magnetic disk during selected periods for postprocessing.

2.3. Data processing

Real-time means, variances, covariances, third and fourth-order moments were computed for half-hour intervals. A digital recursive filter, with a 200 s time constant, was used to compute running means. A one-dimensional coordinate rotation was applied to the wind speed vectors measured inside the canopy, making u the streamwise velocity and v the lateral velocity, with a mean value of zero. A three-dimensional rotation was applied to wind vector measurements made above the canopy. Cosine corrections were not applied to the wind velocity measurements made with the Gill uvw anemometer.

Turbulence statistics evaluated in this paper include turbulence intensity, skewness and kurtosis. Turbulence intensities are defined as:

$$i_x = \sigma_x/\bar{u}\,, \tag{1}$$

where an overbar represents time averaging, x denotes the wind velocity vector (u, v, or w), σ_x is the standard deviation of the wind velocity vector, x, and u is mean horizontal wind speed. Computations of skewness are used to examine third-order moments. Skewness is computed as:

$$Sk_x = \overline{x'^3}/\sigma_x^3\,, \tag{2}$$

where a prime denotes fluctuations from the mean. Skewness values are equal to zero when the probability distribution of x is symmetric. Positive skewness values indicate that there are more large positive excursions from zero than negative excursions, and vice versa. Computations of kurtosis are used to examine fourth-order moments. Kurtosis is computed as:

$$Kr_x = \overline{x'^4}/\sigma_x^4, \tag{3}$$

Kurtosis values equal 3 when the probability distribution of x is Gaussian.

Measurements of higher-order moments can be unreliable unless the length of the sampling period exceeds a theoretical limit or measurements from many sampling periods are used to determine an ensemble average (see Lumley and Panofsky, 1964). The length of the sampling period is a function of the moment of interest. For example, a longer sampling period is needed to measure a fourth moment than a second moment because the fourth moment is weighted heavily in the tails of the distribution and is, thus, strongly affected by infrequent events. Lumley and Panofsky (1964) describe a means for computing the duration of the sampling period as needed to measure a higher-order moment in a turbulent field. The length of the sampling period is a function of the integral time-scale of the turbulence and the desired sampling error. Assuming an integral time constant of 2 s, a typical value measured in the crown of this forest canopy (Baldocchi and Meyers, 1988), and a 15% sampling error, a sampling period of 1896 s is required to measure a statistically confident fourth moment. The sampling period used in this experiment (1800 s) is almost adequate. By pooling averages from many half-hour sampling periods to compute a grand mean, the higher-order moments presented in this paper are statistically stable and have sampling errors of less than or equal to 15%.

The data were separated into daytime and night time periods. Daytime periods were confined between to 0900 to 1700 hr, whereas night time periods included measurements made between 1900 and 0530 hr. Day/night transition periods were avoided. Periods when the wind speed at 34 m was less than 1.0 m s^{-1} were omitted from the analysis. The predominant wind direction was southwesterly (about 225 degrees) and ranged between 180 and 270 degrees; this sector has been documented as having the most uniform fetch at this site, based on previous studies (e.g., Verma *et al.*, 1986). Atmospheric stability, defined as $(z - d)/L$, where z is at 34 m, L is the Monin–Obukhov scale length, and d is the zero-plane displacement height, ranged between near-neutral and slightly unstable (-0.024 ± 0.018) during the day and was slightly stable (0.09 ± 0.014) for the nighttime observations.

3. Results and Discussion

3.1. Mean Vertical Profiles of Statistical Moments

3.1.1. *Horizontal Wind Speed and Tangential Momentum Stress*

Vertical profiles of mean wind speed, normalized by friction velocity at 1.45h ($u_* = -\overline{w'u'}^{0.5}$) are presented in Figure 2. Several features are noted. First, strong wind shear occurs in the upper 20% of the canopy (above 0.8h). Second, a pronounced secondary maximum occurs in the subcanopy, between 0.5h and 0.3h. Third, there is

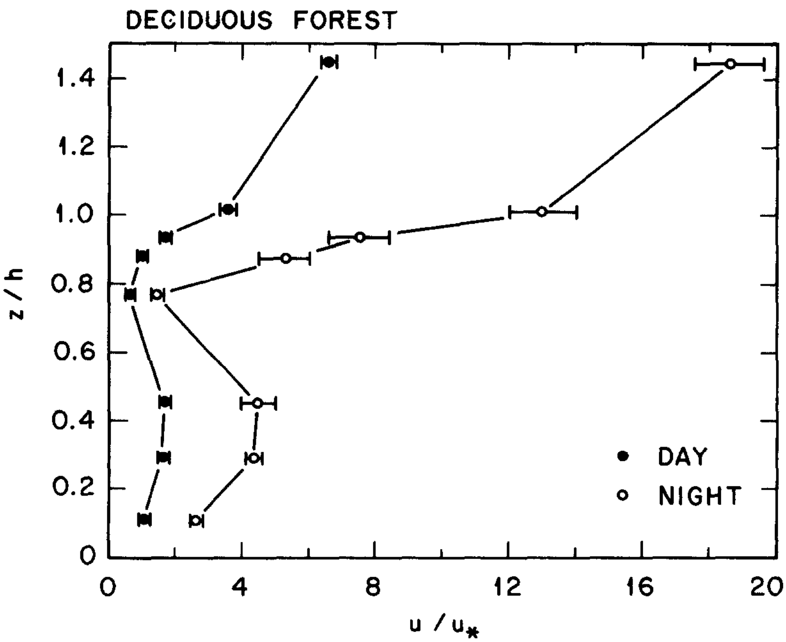

Fig. 2. Vertical variation in streamwise wind velocity, normalized by friction velocity (u_*). Error bars represent the standard error of the mean.

a strong day/night difference in the vertical structure of the mean wind velocity profile (as scaled by u_*).

The occurrence of strong horizontal wind speed shear in the upper 20% of the canopy is a consequence of great absorption of tangential momentum by the dense foliage in the canopy crown (Figure 3); over 90% of the momentum transfer measured at 1.45*h* is absorbed between *h* and 0.8*h*, a region where over 70% of the total canopy leaf area resides (see Figure 1).

Below crown closure, a pronounced secondary wind speed maximum occurs, despite little tangential momentum stress being measured in this region (Figure 3). Theoretically, a secondary wind speed maximum occurs, in a horizontally homogeneous canopy in uniform terrain, when the net convergence of the vertical flux of momentum transfer ($\partial \overline{u'w'w'}/\partial z$) exceeds the pressure destruction term in the $\overline{w'u'}$ budget (Shaw, 1976; Wilson and Shaw, 1977; Meyers and Paw U, 1986). We cannot conclude that the secondary wind speed maximum is not an artifact of the complexity of the local terrain and the heterogeneity of the natural canopy. However, a comparison between these measurements and theoretical estimates of the mean wind velocity, based on a higher-order closure model and the assumption of a horizontally homogeneous canopy (Meyers and Paw U, 1986), yields good agreement (Figure 4). Furthermore, the general features of these wind speed profiles resemble wind profiles measured in uniform forest planta-

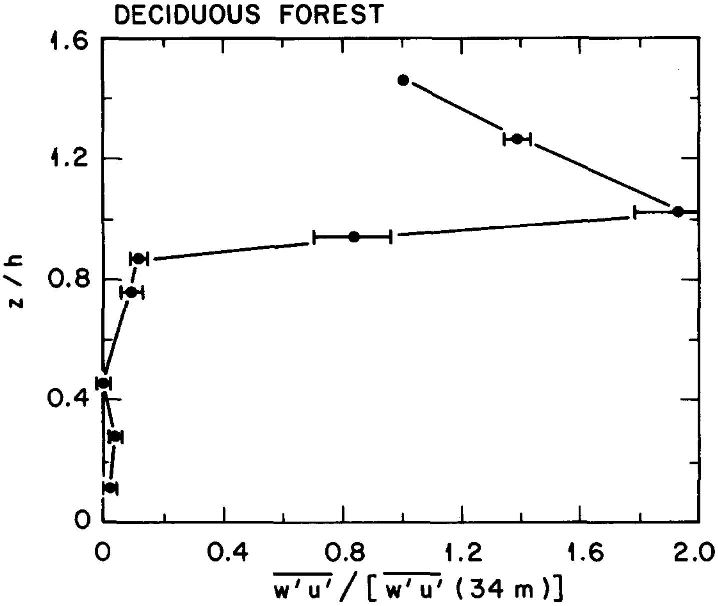

Fig. 3. Vertical variation in tangential momentum stress, normalized by values measured above the canopy (34 m above the ground). Error bars represent the standard error of the mean.

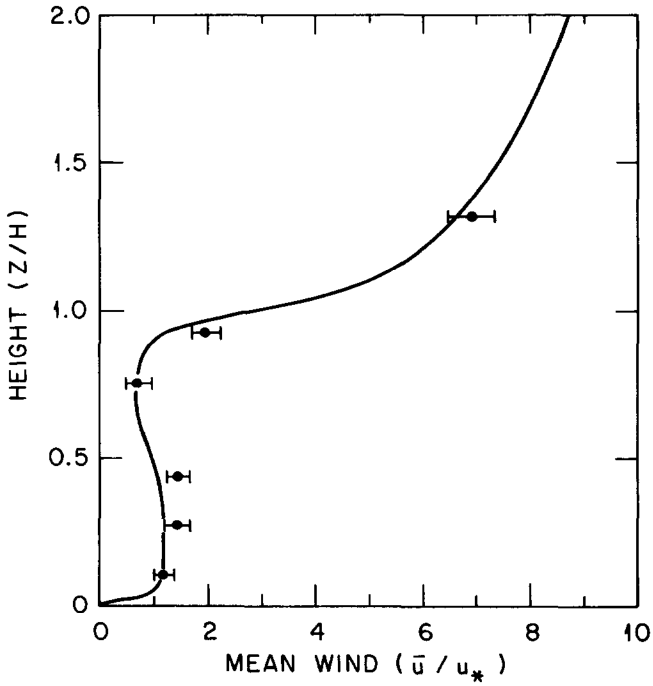

Fig. 4. A comparison between normalized streamwise wind velocities above and within a deciduous forest canopy computed with the higher-order closure model of Meyers and Paw U (1986) and measured. Error bars represent the standard error of the mean.

tions and orchards (larch, Allen, 1968; spruce, Landsberg and James, 1971; orange grove, Kalma and Stanhill, 1972; almond orchard, Baldocchi and Hutchison, 1987); these profiles are characterized by great shear in the upper canopy and a secondary wind speed maximum below crown closure.

The nocturnal shift in the normalized wind profile, represented by an increase in u/u_*, is attributed to the stability of the nocturnal boundary layer which acts to dampen turbulence above and within the canopy. This proposed mechanism is supported by the nocturnal reduction in turbulence intensities measured above and within the canopy (Figure 5) and a corresponding reduction in turbulence variances. Nocturnal stability also reduces tangential momentum stress which leads to lower u_* values at a given wind speed. This phenomenom explains the greater u/u_* values measured at night.

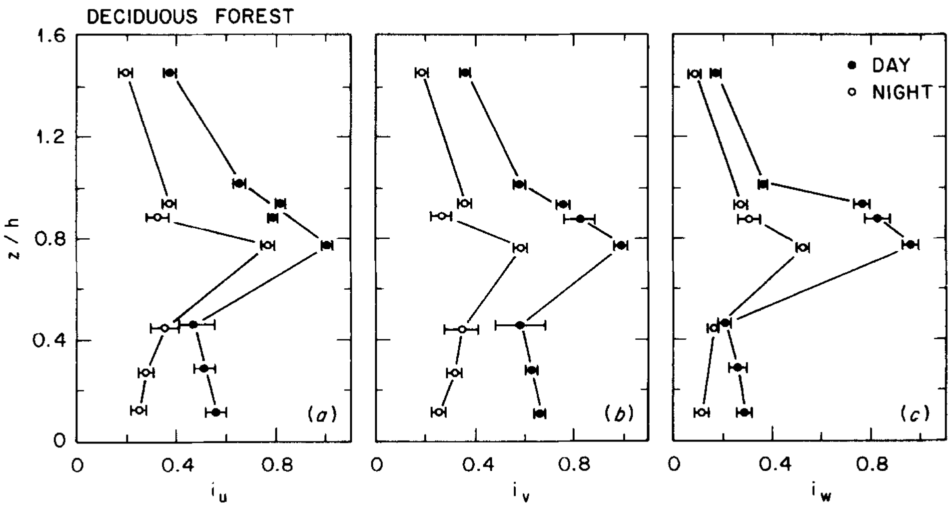

Fig. 5a–c. Vertical profiles of turbulence intensities: (a) Streamwise velocity component. (b) Lateral velocity component. (c) Vertical velocity component. Error bars represent the standard error of the mean.

Theoretical computations by Pereria and Shaw (1977) show that atmospheric stability has little effect on turbulence structure in a relatively short canopy, such as corn. These workers, however, speculated that stability effects may be important in tall forest canopies. These data seem to support their hypothesis.

The zero-plane displacement (d) can be estimated as the level where half of the tangential momentum stress is absorbed (Thom, 1975). Based on this definition, d occurs at about $0.9h$ (Figure 3). Dolman (1986), on the other hand, reports that d is on the order of about $0.75h$ for a European oak forest. The d-value in this North American deciduous forest is also much higher than values reported for agricultural crops, which are on the order of $0.6h$ (Monteith, 1973). Differences among these values are attributed to differences in canopy density and the vertical distribution of foliage (see Shaw and

Pereira, 1982). As Figure 1 shows, the foliage of the canopy was highly concentrated in the upper 20% of the canopy.

A strong gradient in $\overline{w'u'}$ is apparent above the forest canopy (Figure 3). A combination of several factors accounts for this gradient. The vertical variation between 1.45 and 1.30 is partly due to the fact that the Gill uvw anemometer at 1.45h underestimates tangential momentum stress; Hicks (1972) shows that a Gill propellor anemometer underestimates tangential momentum stress by 8 to 25%. Topographic effects also contribute to the vertical gradient in $\overline{w'u'}$ above the canopy. The obstruction to wind flow by a hill causes a pressure perturbation and a convergence of the wind streamlines, which leads to a speed-up in wind at the summit. Theoretically, the sum of the horizontal pressure gradient and the vertical gradient in tagential momentum stress must balance terrain-induced horizontal advection (see Mason, 1986; Zeman and Jensen, 1987). Near the surface of a hill, the streamwise wind flow can be expressed via a simple linearized equation (Mason, 1986):

$$\overline{U}_0(z)\, \partial\overline{u}/\partial x = -\, \partial\overline{p}/\partial x + \partial\overline{w'u'}/\partial z\,, \tag{4}$$

where U_0 is the wind speed of the undisturbed wind flow in the turbulent boundary layer, u is the wind speed of the perturbed wind flow, and p is the dynamic pressure divided by air density. The enhanced values in $\overline{w'u'}$ at 1.02h also results from point-to-point variability in measuring tangential momentum stress near the canopy-atmosphere interface. Several upwind tree crowns protrude above the mean effective canopy height. Local wakes and vortices are tripped by these elements and may lead to larger magnitudes of $\overline{w'u'}$ downwind.

3.1.2. *Turbulence Intensities*

The turbulence intensity profiles exhibit well-defined structure (Figure 5), reflecting the influence of the vertical distribution of foliage. These profiles increase with depth into the canopy, until a maximum occurs at about between 0.8h, and decrease between 0.8h and 0.4h. Below 0.4h, turbulence intensities increase with depth during the day and decrease during the night. During the day, maximum turbulence intensities are on the order of about 1, whereas at night, maximum values range between 0.5 and 0.8. As discussed above, the stability of the nocturnal boundary layer dampens turbulent fluctuations and leads to the nighttime decrease in turbulence intensities. In general, turbulence intensities are similar for the two horizontal wind components and exceed those measured for the vertical component. Smaller turbulence intensities are often associated with the vertical velocity component since the ground surface restricts the size of the vertical eddies (Finnigan, 1979a).

The magnitudes of these values are in broad agreement with those measured in forests (Cionco, 1972) and an almond orchard (Baldocchi and Hutchison, 1987). Smaller values, ranging between 0.2 and 0.8, have been reported for corn (Shaw *et al.*, 1974a), wheat (Finnigan, 1979a), and a larch plantation (Allen, 1968). Wilson *et al.* (1982), on the other hand, report values as large as 4.0 in corn.

3.1.3. *Skewness*

Skewness describes the asymmetry of the probability density distribution. Skewness profiles (Figure 6) are not greatly defined and show little day/night differences. In general, Sk_u values are greater than zero, Sk_w values are less than zero and Sk_v values are near zero inside the canopy. Large skewness values occur between $0.8h$ and the top of the canopy, where foliage density and wind shear are greatest; the maximum magnitude of streamwise skewness is on the order of 1.25. Below this level, the Sk_u and Sk_v profiles are relatively constant and their magnitudes are small. Only the Sk_w profile shows significant vertical structure and day/night differences, with greater magnitudes of Sk_w occurring during the day.

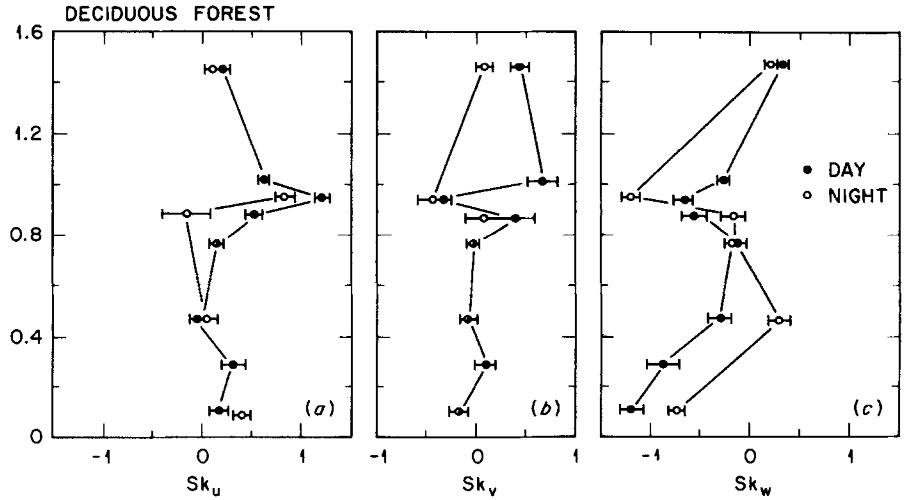

Fig. 6a–c. Vertical profiles of skewness. (a) Streamwise velocity component. (b) Lateral velocity component. (c) Vertical velocity component. Error bars represent the standard error of the mean.

The magnitude and signs of the w and u skewness values resemble those measured in plantations, orchards, crops and artificial canopies (e.g., Allen, 1968; Seginer *et al.*, 1976; Finnigan, 1979b; Shaw and Seginer, 1987; Raupach *et al.*, 1986; Baldocchi and Hutchison, 1987). Sk_u values are positively skewed because intermittent wind gusts penetrate deep into the canopy with velocities greater than the local mean. On the other hand, there is no equivalent source of air moving slower than the mean velocity. Sk_w values are negatively skewed because the greater turbulence intensities in the upper canopy are carried downward with negative vertical velocity fluctuations, whereas near the canopy floor, turbulent motions are suppressed and there is no source for the creation of positive updrafts (see Shaw and Seginer, 1987).

Typically, Sk_w values approach zero near the canopy floor since the ground deflects downward-moving gusts into horizontal motions (Raupach *et al.*, 1986; Baldocchi and

Hutchison, 1987; Shaw and Seginer, 1987). On the contrary, we observe that Sk_w becomes increasingly negative with depth near the canopy floor (Figure 6). This behavior may be an artifact of terrain-following subcanopy flow; this contention is supported below with the profile structure of other higher moment statistics and the cross-correlation analysis of Baldocchi and Meyers (1988), which shows that subcanopy wind flow is more closely coupled with the above-canopy wind flow regime than is wind flow in the canopy crown.

The near-zero Sk_v values, observed below crown closure, are in relative agreement with data of Seginer *et al.* (1976), measured in an artifical canopy, and the theoretical arguments of Shaw and Seginer (1987). On the other hand, larger magnitudes of Sk_v in the canopy crown are probably an artifact of secondary circulations and wake turbulence generated by the upwind trees, as observed in a uniform almond orchard (Baldocchi and Hutchison, 1987).

3.1.4. *Kurtosis*

Kurtosis describes the peakedness or flatness of a probability density distribution. Kurtosis values for the horizontal wind speed components attain a peak, on the order of 6 to 7, in the upper 10% of the canopy, decrease until below crown closure, after which they remain relatively constant, with values on the order of 4 (Figures 7a and 7b). Little day/night differences are observed between the profiles for the u and v components. The kurtosis profiles for the vertical velocity component (Figure 7c) exhibit two peaks, one in the crown and one near the ground surfaces; maximum values are on the order of 8 to 9. The large Kr_w values in the subcanopy trunkspace are attributed to the large intermittant eddies that have sufficient energy to penetrate deep into the canopy.

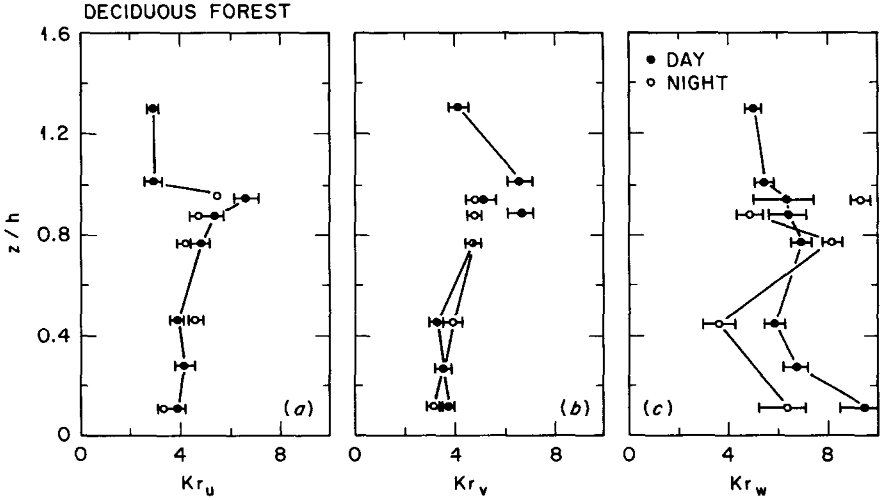

Fig. 7. Vertical profiles of kurtosis. (a) Streamwise velocity component. (b) Lateral velocity component. (c) Vertical velocity component. Error bars represent the standard error of the mean.

The shapes and magnitudes of the kurtosis values are in relative agreement with data from an artificial canopy (Raupach *et al.*, 1986), a larch plantation (Allen, 1968) and an almond orchard (Baldocchi and Hutchison, 1987). The magnitude of these kurtosis values exceed 3, the value on which the quasi-Gaussian approximation is based and which is used in some higher-order closure models (Shaw and Seginer, 1987; Meyers and Paw U, 1986). Recently, Shaw and Seginer (1987) show that the quasi-Gaussian assumption is adequate in third-order closure models. They report that computations of third-order moments are only slightly improved by using measured fourth-order products instead of estimating the fourth-order terms on the basis of the quasi-Gaussian assumption.

3.1.5. *Mixed Third-Order Moments*

Mixed third-order moments arise in the rate equations of the second moments. The terms of interest are $\overline{u'w'w'}$, $\overline{w'v'v'}$, $\overline{w'u'u'}$, and $\overline{u'v'v'}$; other terms arise, $\overline{u'u'v'}$, $\overline{v'w'w'}$, and $\overline{u'v'w'}$, but are conceptually zero (Shaw and Seginer, 1987). Profiles of the normalized, mixed third-order terms are well-defined and exhibit strong gradients inside the canopy (Figure 8a, day; Figure 8b, night). Typically, these mixed terms increase in magnitude until a maximum occurs at about $0.9h$; these maximum values are on the order of about 0.7 during the day and about 0.6 at night. They then decrease with depth and approach zero below crown closure. The only exception is the increase in the $\overline{u'w'w'}$ term with depth near the surface, suggesting an influence of terrain-induced subcanopy transport. In general, the normalized $\overline{w'u'u'}$ and $\overline{w'v'v'}$ terms are negative and the normalized $\overline{u'w'w'}$ and $\overline{u'v'v'}$ terms are positive, which is in experimental and theoretical agreement with the work of Shaw and Seginer (1987) and Raupach *et al.* (1986). The curvature of these profiles and their magnitudes also resemble measured and computed values for corn (Shaw and Seginer, 1987).

Raupach *et al.* (1986) report that the mixed, third-order moments are much smaller than Sk_u in an artificial canopy; at $0.7h$ they found $Sk_u = -4\overline{u'u'w'} = 5\overline{u'w'w'} = -1.5Sk_w$. We find that these ratios are closer to unity: at $0.77h$, $Sk_u = -1.0\overline{u'u'w'} = 1.13\overline{u'w'w'} = -1.50Sk_w$. Differences between Raupach *et al.*'s ratios and our values can probably be attributed to differences in canopy structure and to differences in the intermittency of the atmospheric boundary-layer flow and the wind flow in the wind tunnel.

Significant vertical gradients in the third-order moments above the canopy are observed, with all values approaching zero at $1.30h$. These gradients suggest that a roughness sublayer extends above this tall rough canopy to about $1.30h$. The height of the top of this roughness sublayer is approximately $h + L_t$, where L_t is the transverse length scale of a tree crown (7 to 8 m). Raupach and Legg (1984) show that flux-gradient relationships are invalid in the roughness sublayer because appreciable wake turbulence is generated and substantial turbulence transport occurs. Our data seem to support this contention, for the case of momentum transfer, because the vertical gradient of $\overline{w'u'u'}$, which represents vertical transport, is significantly non-zero in this layer (see Meyers and Baldocchi, 1988).

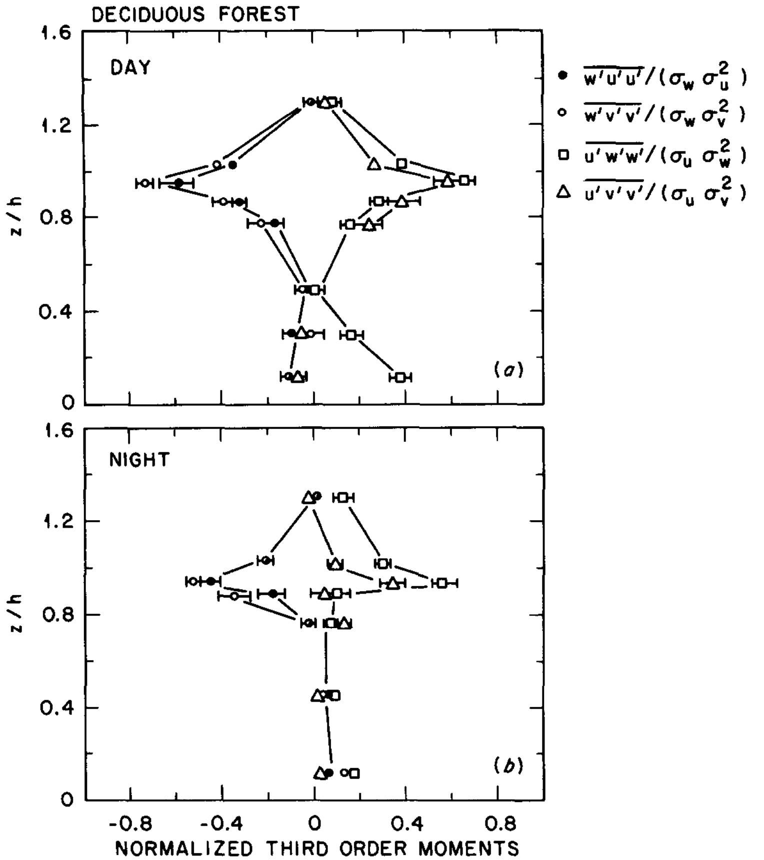

Fig. 8. Vertical profiles of mixed third-order products. These values are normalized by their respective standard deviations. Error bars represent the standard error of the mean.

3.2. Probability density distributions

The occurrence of extreme events can provide important information regarding the liberation of spores, pollen, particles and insects and spiders from leaves (see Shaw *et al.*, 1979; Shaw and McCartney, 1985). These data can also be used to evaluate the probability of windthrow and limb breakage.

Examples of probability density distributions for wind speed components measured above the canopy, in the crown and below crown closure are presented in Figures 9a, 9b, 9c, and 9d for total wind speed (U) and the vertical (w), streamwise (u), and lateral (v) wind speed components, respectively. As suggested by the examination of skewness and kurtosis values, these distributions are distinctly non-Gaussian. In general, the distributions measured inside the canopy are more peaked that those measured above the canopy. Furthermore, wind gusts exceeding a specified threshold are generally more frequent within the canopy than above it (Table II), which is in agreement with the

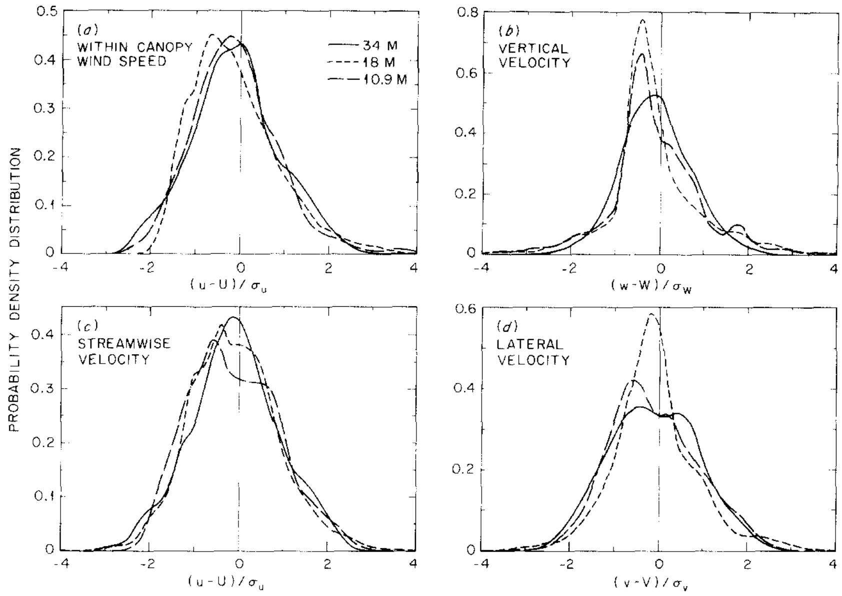

Fig. 9a–d. Probability density distributions of wind speed components. These were measured above the canopy (34 m), in the canopy crown (18 m), and in the subcanopy trunkspace (10.9 m). (a) Wind speed. (b) Vertical velocity component. (c) Streamwise velocity component. (d) Lateral velocity component.

results of Shaw and McCartney (1985). For example, deviations from the mean in scalar wind speeds exceed two times the standard deviation of the mean 2 to 5% of the time within the canopy and less than 2% of the time above the canopy. The liberation of spores, pollen, insects and spiders is affected by the force of a wind gust, which is proportional to the square of wind speed. These data suggest that extreme gusts may occur inside the canopy with sufficient frequency to influence significantly the liberation of these entities.

3.3. Conditional sampling of tangential momentum stress

Conditional sampling of tangential momentum stress provides a means of examining the processes contributing to this transfer. For a detailed discussion of conditional sampling, see Raupach (1981) and Shaw *et al.* (1983). In brief, conditional sampling involves determining the relative contribution of instantaneous products of u' and w' to the computation of mean tangential momentum stress ($\overline{w'u'}$). Four stress quadrants are defined on an established $u - w$ plane where:

Quadrant 1: $u' > 0$, $w' > 0$, outward interactions,
Quadrant 2: $u' < 0$, $w' > 0$, burst or ejection,
Quadrant 3: $u' < 0$, $w' < 0$, inward interactions,
Quadrant 4: $u' > 0$, $w' < 0$, sweep or gust.

To examine the contribution of progressively stronger events to the mean momentum

TABLE IIa

The fractional occurrence of events exceeding ± two standard deviations from the absolute difference of the mean ($|(x - \bar{x})| > 2\sigma_x$)

z/h	w	u	v
1.45	0.011	0.045	0.032
0.94	0.054	0.050	0.054
0.88	0.045	0.045	0.046
0.77	0.057	0.046	0.060
0.46	0.059	0.054	0.019
0.29	0.054	0.044	0.041
0.11	0.053	0.046	0.034

TABLE IIb

The fractional occurrence of events exceeding two standard deviations from the difference of the mean. ($(x - x) > 2\sigma_x$. U is the mean scalar wind speed ($U = (u^2 + v^2 + w^2)^{0.5}$).

z/h	U
1.45	0.018
0.94	0.043
0.88	0.031
0.77	0.036
0.46	0.029
0.29	0.028
0.11	0.020

transfer, an exclusion region or 'hole', H, is specified in the $u - w$ plane such that only those events in each quadrant for which $|u'w'|/|\overline{u'w'}| > = H$ are considered.

The stress fraction is defined as the ratio of the total tangential momentum stress at hole sizes exceeding a particular level to the total tangential momentum stress at all hole sizes. Correspondingly, the time fraction is the ratio of the number of events at hole sizes exceeding a particular level to the total number of turbulent events.

The contributions of different hole sizes to the total time and stress fractions are presented in Figures 10a and 10b. Events exceeding 5 times the mean momentum stress occur less than one-half of the time at all levels within and above the canopy. Yet, these events account for a disproportionate amount of the total momentum transfer. Above the canopy, events exceeding 5 times the mean momentum stress account for about half of the transfer, whereas inside the canopy, these extreme events account for 60 to 90% of mean momentum stress. The contribution of extreme events to momentum transfer peaks at $0.77h$, where at hole size 30, about 65% of the stress fraction is accounted by less than 10% of the events.

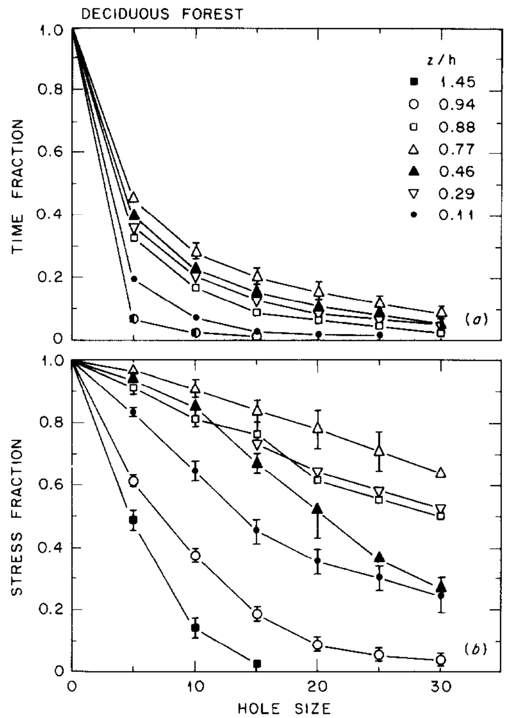

Fig. 10. (a) The time fractions associated with tangential momentum stress at varying hole sizes. (b) The stress fractions associated with tangential momentum stress at varying hole sizes. Error bars represent standard errors of the mean.

The observation that extreme, infrequent events account for a disproportionate amount of tangential momentum stress in a plant canopy has also been observed in corn (Shaw *et al.*, 1983), wheat (Finnigan, 1979b), an almond orchard (Baldocchi and Hutchison, 1987), and an artificial canopy (Raupach, 1981: Raupach *et al.*, 1986). The magnitude of the time and stress fractions at different hole sizes, however, vary due to differences in canopy structure and the anemometry used in the measurements (see Raupach *et al.*, 1986).

The vertical variation of the contribution of each stress quadrant to the mean tangential momentum stress is shown in Figure 11, for hole size zero, which includes all events. Typically, the magnitude of the stress fraction terms is large, often on the order of 1 to 3. This suggests that tangential momentum stress is comprised of the relatively small sum of large contributions from the four stress fractions. Above $0.9h$ and below $0.2h$ most of the stress fraction components are less than 1, representing a contribution by smaller turbulent events.

Finnigan (1979b) and Baldocchi and Hutchison (1987) report similar results; that momentum transfer in plant canopies is the small sum of large offsetting contributions by the four stress fractions. On the other hand, Shaw *et al.* (1983), Raupach (1981), and

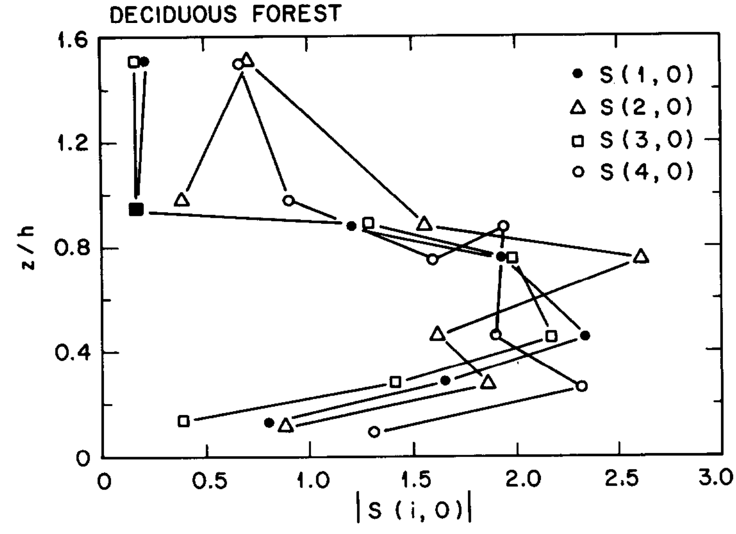

Fig. 11. Vertical profiles of the absolute value of the four stress fractions, associated with tangential momentum stress, at hole size zero.

Raupach *et al.* (1986) report that stress fractions are typically less than one. Large stress fractions (greater than one) are associated with measurements in tall forests or orchards (Figure 11; Baldocchi and Hutchison, 1987) and aeroelastic canopies (Finnigan, 1979b). Smaller stress fractions (less than 1) are measured in shorter and stiffer canopies (Shaw *et al.*, 1983; Raupach *et al.*, 1986).

At most levels, ejections and sweeps (quadrants 2 and 4) provide the dominant mechanism for momentum transfer. One exception is at $0.45h$, where positive momentum stress is observed. Here, outward and inward interactions dominate the transfer processes. These results suggest the advection of momentum, the presence of wake turbulence or a secondary circulation.

Typically, weeps exceed ejections by a factor ranging between 1.1 and 2.3. An exception is $0.77h$ where ejections exceed sweeps; the sweep-to-ejection ratio is about 0.60. Shaw *et al.* (1983) report sweep-to-ejection ratios on the order of 1 and 3 and Finnigan (1979b) reports values ranging between 3 and 4. The larger sweep-to-ejection ratios reported by Finnigan (1979b) have been criticized by Raupach *et al.* (1986b). They argue that the X-wire anemometry used by Finnigan overestimates the sweep-to-ejection ratio when turbulence intensities are high, as is commonly observed in plant canopies.

Shaw *et al.* (1983) define exuberance as the ratio $(S(1,0) + S(3,0))$ to $(S(2,0) + S(4,0)$, where quadrants 1 and 3 represent events contributing to an upward transfer of momentum and quadrants 2 and 4 represent downward transfer. Shaw *et al.* (1983) report relatively small exuberance values, ranging between about -0.13 and -0.19, within corn. Our values range between about -0.3 and -0.8 and are similar to those reported by Finnigan (1979b) for wheat. Finnigan (1979b) attributes this high exurberance to the waving motion of the stalks. However, Shaw *et al.* (1983) question this supposition since Finnigan's (1979b) exuberance values were least in the upper canopy where the waving motion of the canopy is greatest. A more practical explanation for large exuberance values in this forest and wheat may probably be found by relating the exuberance to the complexity of within-canopy wind flow, generated by wake turbulence and secondary circulations, which lead to significant inward and outward interactions.

The vertical variation of the time fraction observed in each quadrant shows an equitable contribution to the turbulent transfer of momentum (Figure 12). Typically, stress events occur about 20 to 30% of the time in each quadrant. These results agree with measurements made in an almond orchard (Baldocchi and Hutchison, 1987).

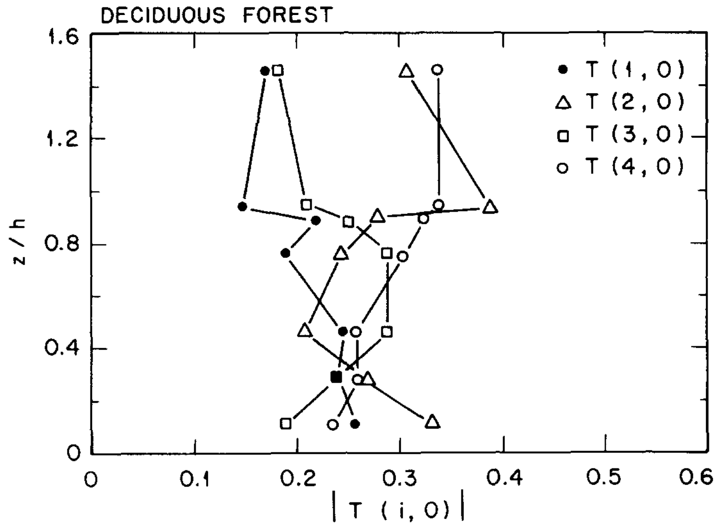

Fig. 12. Vertical profiles of the four time fractions, associated with tangential momentum stress, at hole size zero.

4. Summary

Detailed vertical structure of turbulence statistics, measured in a deciduous forest, are presented. Vertical profiles of the turbulence statistics reflect the dominating influence of the vertical distribution of canopy foliage, stems and trunks; strong shear and large turbulence intensities, skewness and kurtosis values are observed in the upper 20% of the canopy, where over 70% of the foliage exists. Examination of these statistics and conditional sampling of tangential momentum stress reveals that exchange processes in the canopy are dominated by large intermittent eddies.

Significant day/night differences were observed in the shape of the wind speed and turbulence intensity profiles. These features reflect the influence of the stability of the atmospheric boundary layer.

We cannot estimate with confidence the magnitude of the influence of complex terrain and canopy heterogeneity on the turbulent statistics in this forest. Wind speed profiles seem to agree with computations based on the assumption of a horizontal, homogeneous canopy. Yet, there is some indication, by the shape of the third-order moment (Sk_w, $\overline{u' w' w'}/\sigma_u \sigma_w^2$) profiles, that there may be some terrain-induced effects on the subcanopy wind flow.

Future studies are needed to examine the horizontal variability of turbulence in the canopy and the role of complex terrain.

Acknowledgements

This work was partially sponsored by the National Oceanic and Atmospheric Administration and the U.S. Department of Energy.

We are grateful to John Wilson, Carmen Nappo and Ron Dobosy, for their careful reviews and comments.

References

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

Baldocchi, D. D. and Hutchison, B. A.: 1987, 'Turbulence in an Almond Orchard: Vertical Variation in Turbulent Statistics', *Boundary-Layer Meteorol.* **40**, 177–146.

Baldocchi, D. D. and Hutchison, B. A.: 1988, 'Turbulence in an Almond Orchard: Spatial Variation in Spectra and Coherence', *Boundary-Layer Meteorol.* **42**, 293–311.

Baldocchi, D. D. and Meyers, T. P.: 1988, 'A Spectral and Lag-Correlation Analysis of Turbulence in a Deciduous Forest Canopy', *Boundary-Layer Meteorol.* (submitted).

Cionco, R. M.: 1972, 'Intensity of Turbulence within Canopies with Simple and Complex Roughness Elements', *Boundary-Layer Meteorol.* **2**, 453–465.

Dolman, A. J.: 1986, 'Estimates of Roughness Length and Zero-Plane Displacement for a Foliated and Non-Foliated Oak Canopy', *Agric. Forest Meteorol.* **36**, 241–248.

Finnigan, J. J.: 1985, 'Turbulent Transport in Flexible Plant Canopies', in B. A. Hutchison and B. B. Hicks (eds.), *Forest Atmosphere Interactions*, D. Reidel Publ. Co. Dordrecht, Holland, pp. 443–480.

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

Finnigan, J. J.: 1979b, 'Turbulence in Waving Wheat. II. Structure of Momentum Transfer', *Boundary-Layer Meteorol.* **16**, 213–236.

Hicks, B. B.: 1972, 'Propellor Anemometers as Sensors of Atmospheric Turbulence', *Boundary-Layer Meteorol.* **3**, 214–228.

Hutchison, B. A., Matt, D. R., McMillen, R. T., Gross, L. J., Tajchman, S. J., and Norman, J. M.: 1986, 'The Architecture of an East Tennessee Deciduous Forest Canopy', *J. Ecol.* **74**, 635–646.

Kalma, J. D. and Stanhill, G.: 1972, 'The Climate of an Orange Orchard: Physical Characteristics and Microclimate Relationships', *Agric. Meteorol.* **10**, 185–201.

Landsberg, J. J. and James, G. B.: 1971, 'Wind Profiles in Plant Canopies, Studies of an Analytical Model', *J. Appl. Ecology* **8**, 729–741.

Legg, B. J. and Raupach, M. R.: 1982, 'Markov–Chain Simulation of Particle Dispersion in Inhomogeneous Flows: the Mean Drift Velocity Induced by a Gradient in Eulerian Velocity Variance', *Boundary-Layer Meteorol.* **24**, 3–13.

Lumley, J. L. and Panofsky, H. A.: 1964, *The Structure of Atmospheric Turbulence*, Interscience-Wiley, New York, 239 pp.

Mason, P. J.: 1986, 'Flow over the Summit of an Isolated Hill', *Boundary-Layer Meteorol.* **37**, 385–405.
Meyers, T. P. and Paw U, K. T.: 1986, 'Testing of a Higher Order Closure Model for Modeling Airflow within and above Plant Canopies', *Boundary-Layer Meteorol.* **37**, 297–311.
Meyers, T. P. and Baldocchi, D. D.: 1988, 'The Budgets of Turbulent Kinetic Energy and Momentum Flux within and above a Forest Canopy', (in preparation).
Monteith, J. L.: 1973, *Principles of Environmental Physics*, E. Arnold Ltd., London, 241 pp.
Pereira, A. R. and Shaw, R. H.: 1977, 'A Simulation on the Effects of Buoyancy on Canopy Flow', *Proc. 13th Conf. on Agric. and Forest Meteorology*, Am. Meteorol. Soc. Boston, pp. 109–110.
Raupach, M. R.: 1987, 'A Lagrangian Analysis of Scalar Transfer in Vegetation Canopies', *Quart. J. Roy. Meteorol. Soc.* **113**, 107–120.
Raupach, M. R.: 1981, 'Conditional Statistics of Reynold's Stress in Rough Wall and Smooth Wall Turbulent Boundary Layers', *J. Fluid Mech.* **108**, 363–382.
Raupach, M. R. and Legg, B. J.: 1984, 'The Uses and Limitations of Flux-Gradient Relationships in Micrometeorology', *Agric. Water Magnement* **8**, 119–131.
Raupach, M. R. and Shaw, R. H.: 1982, 'Averaging Procedures for Flow within Vegetation Canopies', *Boundary-Layer Meteorol.* **22**, 79–90.
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.
Shaw, R. H.: 1976, 'Secondary Wind Maxima Inside Plant Canopies', *J. Appl. Meteorol.* **16**, 514–521.
Shaw, R. H. and Pereira, A. R.: 1982, 'Aerodynamic Roughness of a Plant Canopy: a Numerical Experiment', *Agric. Meteorol.* **26**, 51–65.
Shaw, R. H. and McCartney, H. A.: 1985, 'Gust Penetration Into Plant Canopies', *Atmos. Envir.* **19**, 827–830.
Shaw, R. H. and Seginer, I.: 1987, 'Calculation of Velocity Skewness in Real and Artifical Plant Canopies', *Boundary-Layer Meteorol.* **39**, 315–332.
Shaw, R. H. and Seginer, I.: 1985, 'The Dissipation of Turbulence in Plant Canopies', *7th Symp. on Turbulence and Diffusion*, Am. Meteorol. Soc. Boston, pp. 200–203.
Shaw, R. H., den Hartog, G., King, K. M., and Thurtell, G. W.: 1974a, 'Measurements of Mean Wind Flow and Three-Dimensional Turbulence Intensity with a Mature Corn Canopy', *Agric. Meteorol.* **13**, 419–425.
Shaw, R. H., Silversides, R. H., and Thurtell, G. W.: 1974b, 'Some Observations of Turbulence and Turbulent Transport within and above Plant Canopies', *Boundary-Layer Meteorol.* **5**, 429–449.
Shaw, R. H., Tavangar, J., and Ward, D. P.: 1983, 'Structure of the Reynold's Stress in a Canopy Layer', *J. Climate Appl. Meteorol.* **22**, 1922–1931.
Shaw, R. H., Ward, D. P., and Aylor, D. E.: 1979, 'Frequency of Occurrence of Fast Gusts of Wind Inside a Corn Canopy', *J. Appl. Meteorol.* **18**, 161–171.
Thom, A. S.: 1975, 'Momentum, Mass, and Heat Exchange of Plant Communities', J. L. Monteith (ed.), *Vegetation and the Atmosphere*, Vol. 1, Academic Press. London, pp. 57–109.
Verma, S. B., Baldocchi, D. D., Anderson, D. E., Matt, D. R., and Clement, R. J.: 1986, 'Eddy Fluxes of CO_2, Water Vapor and Sensible Heat over a Deciduous Forest', *Boundary-Layer Meteorol.* **36**, 71–91.
Wilson, J. D., Thurtell, G. W., and Kidd, G. E.: 1981, 'Numerical Simulation of Particle Trajectories in Inhomogeneous Turbulence. I. Systems with Constant Turbulent Velocity Scales', *Boundary-Layer Meteorol.* **21**, 295–313.
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.
Wilson, N. R. and Shaw, R. H.: 1977, 'A Higher-Order Closure Model for Canopy Flow', *J. Appl. Meteorol.* **16**, 1197–1205.
Wyngaard, J. C. and Zhang, S. F.: 1985, 'Transducer-Shadow Effects on Turbulence Spectra Measured by Sonic Anemometers', *J. Atmos. Oceanic Tech.* **2**, 548–558.
Zeman, O. and Jensen, N. O.: 1987, 'Modification of Turbulence Characteristics in Flow over Hills', *Quart. J. Roy. Meteorol. Soc.* **113**, 55–80.