ATMOSPHERIC TURBULENCE WITHIN AND ABOVE A DOUGLAS-FIR STAND. PART I: STATISTICAL PROPERTIES OF THE VELOCITY FIELD

XUHUI LEE and T. ANDREW BLACK

Department of Soil Science, University of British Columbia, Vancouver, B.C., Canada V6T 1Z4

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Abstract. This is the first of two papers reporting the results of a study of the turbulence regimes and exchange processes within and above an extensive Douglas-fir stand. The experiment was conducted on Vancouver Island during a two-week rainless period in July and August 1990. The experimental site was located on a 5° slope. The stand, which was planted in 1962, and thinned and pruned uniformly in 1988, had a (projected) leaf area index of 5.4 and a height $h = 16.7$ m. Two eddy correlation units were operated in the daytime to measure the fluctuations in the three velocity components, air temperature and water vapour density, with one mounted permanently at a height of 23.0 m ($z/h = 1.38$) and the other at various heights in the stand with two to three 8-hour periods of measurement at each level. Humidity and radiation regimes both above and beneath the overstory and profiles of wind speed and air temperature were also measured. The most important findings are:

(1) A marked secondary maximum in the wind speed profile occurred in the middle of the trunk space (around $z/h = 0.12$). The turbulence intensities for the longitudinal and lateral velocity components increased with decreasing height, but the intensity for the vertical velocity component had a maximum at $z/h = 0.60$ (middle of the canopy layer). Magnitudes of the higher order moments (skewness and kurtosis) for the three velocity components were higher in the canopy layer than in the trunk space and above the stand.

(2) There was a 20% reduction in Reynolds stress from $z/h = 1.00$ to 1.38. Negative Reynolds stress or upward momentum flux persistently occurred at $z/h = 0.12$ and 0.42 (base of the canopy), and was correlated with negative wind speed gradients at the two heights. The longitudinal pressure gradient due to the land–sea/upslope–downslope circulations was believed to be the main factor responsible for the negative Reynolds stress.

(3) Momentum transfer was highly intermittent. Sweep and ejection events dominated the transfer at $z/h = 0.60$, 1.00 and 1.38, with sweeps playing the more important role of the two at $z/h = 0.60$ and 1.00 and the less important role at $z/h = 1.38$. But interaction events were of greater magnitude than sweep and ejection events at $z/h = 0.12$ and 0.42.

1. Introduction

The understanding of forest canopy-atmosphere exchange is of great importance to a variety of scientific issues, such as global and regional CO_2 and water balances, and the transport, dispersion and deposition of air borne pollutants. The conventional gradient-diffusion relationship, or K-theory, has been used for many years to study the exchange processes near the surface of the earth. However, experimental studies in the past two decades have shown that turbulent exchange in the upper part of and immediately above forests and plant canopies of other types is dominated by large intermittent eddies. Because the sizes of these eddies are comparable to canopy height, which is the scale of scalar concentration and velocity gradients,

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the validity of K-theory is questionable. In recent years, much attention has been directed to alternative approaches, such as random flight simulations in a Lagrangian framework (e.g., Leclerc *et al.*, 1988; Legg *et al.*, 1986; Legg and Raupach, 1982) and higher order closure models (Meyers and Paw U, 1986; Wilson, 1988; Wilson and Shaw, 1977). These theories are, however, still at an early stage of development. More experimental studies are required to provide data for testing and further development of the theories.

Recently experiments have been conducted on atmospheric turbulence in forest stands of various tree species, e.g., in mixed deciduous forests of oak and hickory trees (Baldocchi and Meyers, 1988) and of mainly aspen and red maple trees (Shaw *et al.*, 1988), in a forest of pine trees (Denmead and Bradley, 1985), and in forests of aspen, pine and spruce trees (Amiro, 1990a, b). In this work, a coastal coniferous forest of Douglas-fir trees on Vancouver Island was selected as the site for a turbulent exchange experiment.

Douglas-fir is an important tree species in the northwest coastal region of North America. In western Oregon, Washington and British Columbia, Douglas-fir occupies about 15.8 million hectares (Oliver *et al.*, 1986). The process of evapotranspiration from Douglas-fir stands has been studied extensively using the energy balance approach to examine the validity of Monteith's big leaf model (Monteith, 1965) or its modified versions (e.g., Kelliher *et al.*, 1986; Tan and Black, 1976; McNaughton and Black, 1973; Fritschen *et al.*, 1985). Yet relatively little is known about turbulent characteristics of the air flow and the exchange processes within and above the forests of this type. The overall goal of the study reported here is to examine in detail the turbulence regimes and the exchange processes within and immediately above the selected stand. The study is part of a collaborative research project which aimed to develop silvicultural prescriptions that would satisfy timber production objectives while creating black-tailed deer winter range on Vancouver Island. It is also intended to contribute to an improved understanding of the exchange processes in forest environments in general.

This paper is the first of two reporting the results of the data analysis of the study. The second paper (Lee and Black, 1993, hereafter referred to as II) concentrates on the eddy fluxes of sensible heat and water vapour within and above the stand. This paper is limited to the statistical properties of the velocity field within and above the stand. Specifically, the objectives of this paper are: (1) to document the stability regimes using the Monin–Obukhov length scale and to examine the applicability of Monin–Obukhov scaling above the stand; (2) to describe the statistics of the velocity of the field, including mean wind speed, Reynolds stress, variance, turbulence intensity, skewness, and kurtosis, with discussion of the mechanism of momentum transfer in the lower part of the stand; and (3) to quantify the intermittency and identify the kinds of turbulent motion which dominate momentum transfer using the quadrant-hole conditional sampling technique.

2. Experimental Methods

2.1. Site description

The experiment was performed in late July and early August, 1990 in a coniferous stand near Browns River located about 10 km west of Courtenay on Vancouver Island, 125°10′ W, 49°42′ N, at an elevation of 450 m. The overstory species is Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), planted in 1962. In 1988, it was thinned to 575 stems/ha and pruned to a height of approximately 6 m uniformly over a 600 × 600 m plot. The forest floor was littered with dead branches and tree trunks, with a little understory vegetation (salal, Oregon grape and huckleberry) less than 0.5 m tall. The average trunk diameter at a height of 1.3 m was 0.20 m. A visual inspection from the instrument tower provided an estimate of 16.7 m for the height of the stand (h). Surrounding the plot are unthinned and unpruned stands of Douglas-fir trees of similar age and height which extend several kilometres.

The profile of the leaf area density of the stand was obtained from intensive destructive sampling on four trees of selected sizes. A branch was sampled every two whorls. The base diameter of all branches on the four trees and the diameter at a height of 1.3 m of 250 trees were measured. The area of needle samples pressed between two glass plates was measured with a video-camera image analysis system (Skye Instruments Ltd., Liandrindod Wells, UK). Leaf area density of the stand was obtained from the relationships between dry needle weight (dried for 8 h at 80 °C) and the projected needle area, between branch diameter and dry needle weight, and between tree diameter and foliage area per tree. The profile of leaf area density is presented in Figure 1. The total (projected) leaf area was 5.4.

The experimental site is located on an east-facing slope with an inclination angle of approximately 5°. The coastline is located 12 km to the east of the site and is oriented in a SE–NW direction. Topographic maps of the site are given in Lee (1992). About 350 m to the east of the instrument tower, the pruned plot ends and the slope becomes steeper (12°). About 60 m to the west of the tower, there is a very narrow silvicultural access road; beyond this the canopy is rather sparse. Farther to the west, at a distance of approximately 500 m, is a small hill. During the daytime, the wind blows constantly from the NE to ENE as a result of sea-to-land and upslope winds. At night, the wind direction is SW to WSW.

The most recent rainfall event prior to the experiment occurred on 6 July, 1990. The weather remained mostly clear during the experimental period. Table I lists the daytime average values of weather variables for the nine days of the experiment.

2.2. Instrumentation and data collection

Micrometeorological measurements were made mainly from a 25 cm wide, 24 m tall guyed triangular open-lattice steel tower. Two eddy correlation units, which

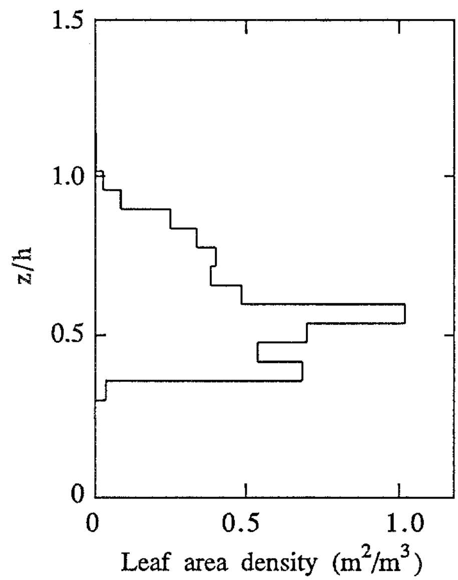

Fig. 1. Profile of leaf area density of the Douglas-fir stand at Browns River. The total (projected) leaf area index was 5.4.

TABLE I

Average values of weather variables at $z/h = 1.38$ for the period 06:00–18:00 PST, the period of operation of the eddy correlation units, and the relative height of the lower eddy correlation unit (z/h) for the Douglas-fir stand at Browns River. $\bar{S}$, $\bar{U}$, $\bar{T}_a$ and $\bar{r}_h$ represent global solar irradiance (horizontal surface), wind speed measured with a cup anemometer, air temperature and relative humidity (average water vapour pressure divided by saturated water vapour pressure at $\bar{T}_a$), respectively. The height of the stand (h) was 16.7 m

Date	Period Hour (PST)	z/h	$\bar{S}$ W/m^2	$\bar{U}$ m/s	$\bar{T}_a$ °C	$\bar{r}_h$ %	Sky
19 Jul	11:30–18:00	0.12	655	2.1	22.8	37	clear
20 Jul	09:30–16:30		646	2.1	24.7	28	clear
26 Jul	09:00–16:30		501	1.8	16.4	73	partly cloudy
27 Jul	11:00–17:30	0.42	637	2.4	17.6	61	clear
28 Jul	08:30–16:00		622	1.7	21.2	51	clear
29 Jul	12.00–19.00	0.60	619	1.7	24.7	39	clear
30 Jul	09:00–16:30		578	2.0	24.5	44	clear
31 Jul	12:30–17:30	1.00	524	1.8	19.3	64	mainly clear
1 Aug	09:00–17:00		548	1.9	16.5	64	partly cloudy

measured the fluctuations in the three velocity components, air temperature and water vapour density, were mounted 1.5 m from the tower. The first unit (hereafter referred to as the upper unit) consisted of one 3-dimensional sonic anemometer

(Applied Technologies Inc., Boulder, CO, Model BH-478B/3, 25 cm path length), one fine-wire thermocouple (chromel-constantan, 13 μm in diameter) and one krypton hygrometer (Campbell Scientific Inc., Logan, UT, Model K20, 0.795 cm path length). This unit was operated permanently at a height of 23.0 m (z/h = 1.38) during the experimental period. The second unit (hereafter referred to as the lower unit) consisted of one 3-dimensional sonic anemometer/thermometer (Applied Technologies Inc., Model SWS-211/3V, 10 cm path length) and one krypton hygrometer (Campbell Scientific Inc., Model K20, 1.021 cm path length). It was operated at the following heights (z/h in brackets): 2.0 (0.12), 7.0 (0.42), 10.0 (0.60), and 16.7 m (1.00) (see Table I).

The analogue voltage signal from the thermocouple of the upper unit was amplified by an amplifier (Neff Instrument Corp., Duarte, CA, Model SC019) with a gain of 2000 and a bandwidth of 10 Hz. The six analogue signals (five from the upper unit and one from the hygrometer of the lower unit) were sent to an A/D board built in the electronics of the sonic anemometer/thermometer of the lower unit, resulting in a total of ten channels of digital data with a sampling rate of 9.9 Hz. The data were sent via a serial port to a lap-top XT micro-computer (Zenith Data Systems Corp., St. Joseph, MI, Model ZWL-184-02 Supersport with 20 Mb hard drive), and transferred to 80 Mb data cartridge magnetic tapes using a tape backup system (Colorado Memory Systems Inc., Loveland, CO, Model DJ-10), usually after a period of about 8 h of continuous data collection, for subsequent analysis. In addition, the analogue signals from the upper unit were sampled in parallel at 10 Hz by a data logger (Campbell Scientific Inc., Model 21X with extended software II), which gave on-line calculations of the most important mean statistics for the purpose of monitoring the performance of the unit.

Turbulence statistics were calculated over 30-min intervals after the experiment. A two-way coordinate rotation was applied to the statistics above and on top of the stand, following the procedure of Tanner and Thurtell (1969), and a one-way coordinate rotation was applied to the statistics inside the stand, following the procedure of Baldocchi and Hutchison (1987).

Air temperature and wind speed were measured continuously over the whole experimental period with fine-wire thermocouples (chromel-constantan, 26 μm in diameter) and sensitive cup anemometers (C. W. Thornthwaite Associates, Centerton, NJ, Model 901–LED), respectively, at heights of 0.9, 2.0, 4.6, 7.0, 10.0, 12.7, 16.7, and 23.0 m. Supporting measurements included humidity, wind direction, and radiation (net, global and diffuse solar irradiances) above the stand and near the forest floor (see II for details). The data logging for these instruments was accomplished by using five additional data loggers (Campbell Scientific Inc., Models 21X and CR5). All data-logging systems were synchronized to within a few seconds. The spatial layout of the instruments used in the experiment was described by Lee (1992).

Eddy correlation sensors were pointed into the prevailing wind direction in the

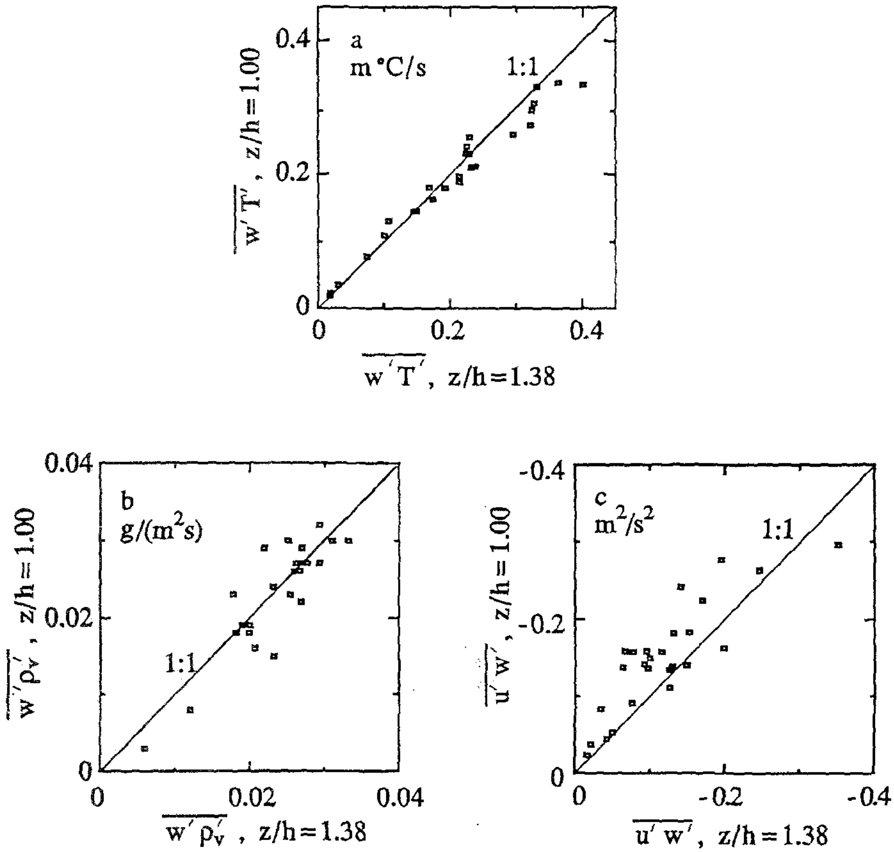

Fig. 2. Covariances of w and T (a), w and ρ_v (b), and w and u (c) measured at $z/h = 1.00$ versus those measured at $z/h = 1.38$ for the Douglas-fir stand at Browns River on 31 July and 1 August 1990.

daytime. Only the turbulence data collected in the daytime were considered for analysis.

2.3. Inter-comparison of Instruments

On 31 July and 1 August 1990, the lower unit was operated at the height of the tree tops ($z/h = 1.00$). Figure 2 shows the 30-min covariances measured at $z/h = 1.00$ plotted against those measured at $z/h = 1.38$. There was good agreement between the two units in the measurement of $\overline{w'T'}$, the covariance between the vertical velocity component (w) and air temperature (T). For $\overline{w'\rho_v'}$, the covariance between w and water vapour density (ρ_v), the scatter was somewhat larger, but overall was about the 1:1 line. A reduction of 20% was observed in $-\overline{u'w'}$, the covariance between the longitudinal velocity component (u) and w or the kinematic Reynolds stress, from $z/h = 1.00$ to $z/h = 1.38$. A decrease in Reynolds stress with increasing height was also observed by Baldocchi and Meyers (1988) over a deciduous forest, with a higher reduction rate of 48% from $z/h = 1.00$ to $z/h = 1.45$. They suggested that one of the reasons for the decrease was the vertical divergence of Reynolds stress associated with the pressure perturbations and convergence of streamlines due to topographic effects, which was also likely to be a contributing factor in the present study. As pointed out later, the longitudinal pressure gradient due to land–sea/upslope–downslope circulations might also contribute to the vertical divergence of Reynolds stress.

In order to compare the measurements made by the sonic anemometers with the measurements made by the cup anemometers, the equivalent average 'cup' wind speed, V was calculated for the sonic anemometers for every 30-min period using

$$V = \overline{\sqrt{u_1^2 + v_1^2}}$$

where u_1 and v_1 are the two horizontal components of the instantaneous velocity vector, and the overbar denotes temporal averaging. The results are summarized in Figure 3. The correlations between V and U, the 30-min average wind speed measured with cup anemometers, were very good, indicating a stable performance of the instruments. But overall the value of U was higher than that of V, which was likely the result of overspeeding of the cup anemometers in turbulent flow (Coppin, 1982).

Concern was expressed about the aerodynamic shadow effect of the rings of the 3-dimensional sonic anemometer of the lower eddy correlation unit. To assess the shadow effect, the two eddy correlation units were compared over a smooth bare field on level ground on 3 and 5 October, 1991 (Lee, 1992). Excellent agreement was obtained for sensible and latent heat fluxes. Wind speed measured with the lower unit was found to be slightly lower (by 4%) than that measured with the upper unit. The value of kinematic Reynolds stress during this comparison was in the range 0.03 to 0.08 m^2/s^2, with $-\overline{u'w'}$ measured using the lower unit being about 20% lower than that measured using the upper unit, which was likely a result of the shadow effect of the rings of the sonic probe of the lower unit on the measurements of the horizontal velocity components.

It should be pointed out that the probe of the sonic anemometer in the lower unit was designed primarily for turbulence measurements in crop and forest canopies where the wind speed is low and wind direction highly unpredictable. According to J. C. Kaimal (1991, personal communications), occasional sweeps by the wakes across an acoustic path that result from the constantly changing wind speed and direction in a plant canopy, will have minimal shadow effect on the measurement. The wind direction during this comparison, on the other hand, was rather steady due to the sea breeze at the experimental site and was mainly directed along the central axis of the probe (the 'worst-case scenario', Kaimal, 1991). No attempt was made to correct the data obtained in our experiment for the shadow effect. But even with the correction based on these worst-case scenario results, the conclusions of this paper would not be altered.

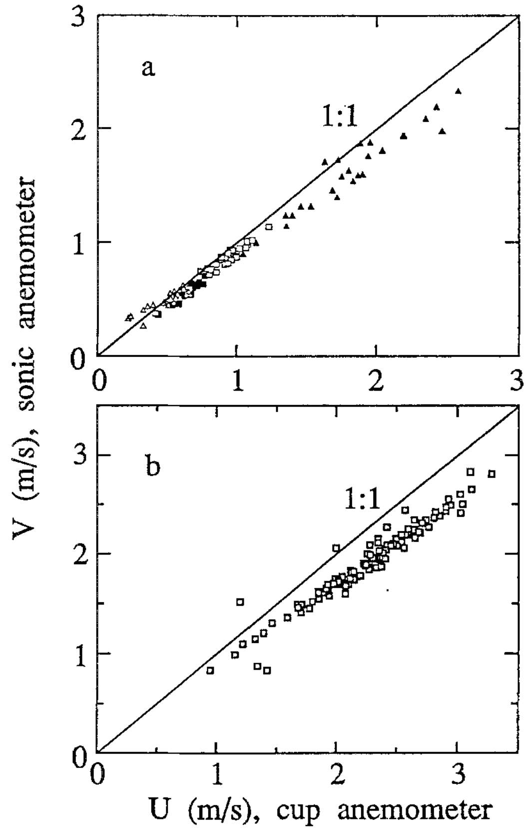

Fig. 3. Comparison of equivalent 'cup speed' V measured by sonic anemometers with wind speed U measured by cup anemometers at the Douglas-fir stand at Browns River during the entire experimental period in 1990: (a) lower unit at $z/h = 0.12$ (□), 0.42 (■), 0.60 (△) and 1.00 (▲) ($R^2 = 0.983$) and (b) upper unit at $z/h = 1.38$ ($R^2 = 0.937$).

3. Results and Discussion

3.1. Monin–Obukhov similarity above the stand

The surface boundary layer over an extensive plant canopy can be considered as comprised of two parts: the upper part, the inertial sublayer (Tennekes, 1973) in which the flux-gradient relationships established on the basis of Monin–Obukhov similarity are obeyed, and the lower part, the roughness sublayer (Raupach *et al.*, 1980) or transition sublayer (Garratt, 1980), which is close to and within the canopy itself (Raupach and Thom, 1981). Three kinds of surface influence in the roughness sublayer have been identified. First, there exists horizontal inhomogeneity, dramatically demonstrated by the horizontal variations in the wind profile over artificial canopies in wind tunnels (Mulhearn and Finnigan, 1978, Raupach *et al.*, 1986), although there do not appear to be any measurements of either wind speed or scalar concentrations over outdoor canopies reported to confirm this feature. Second, the transfer processes in the roughness sublayer are greatly enhanced, with the enhancement effect greater for scalars than for momentum. This feature was attributed to a 'wake production effect' (Thom *et al.*, 1975). It has been observed over a variety of forests (Garratt, 1978a, 1980; Shuttleworth, 1989; Thom *et al.*,1975, Raupach 1979; Denmead and Bradley, 1985; Högström *et al.*, 1989), over a model canopy in a wind tunnel (Raupach *et al.*, 1980), and over bushland (Chen and Schwerdtfeger, 1989). Third, counter-gradient fluxes can occur in the roughness sublayer under certain circumstances (Chen and Schwerdtfeger, 1989).

Garratt (1980) proposed a scaling law, $z_* - d = 3D$, for momentum flux, where z_* is the height (above the ground surface) of the top of the roughness sublayer, d is the height of the displacement plane (assumed to be $0.7h$ in the present study; see Jarvis *et al.*, 1976) and D is the spacing of roughness elements. The mean tree spacing in the stand of the present study is about 4.2 m. Based on Garratt's proposal, the top two measurement levels ($z/h = 1.00$ and 1.38) were located within the roughness sublayer. With sensible heat flux being the dominant output component of the energy budget of the stand (II) and relatively low wind speed, the stability parameter, $(z - d)/L$, where L is the Monin–Obukhov length, was typically of large magnitude, the value varying mainly between -0.20 and -5.0 at $z/h = 1.38$. Eddy diffusivities under these moderately to strongly unstable conditions, calculated from the profile measurements at $z/h = 1.00$ and 1.38 and the flux measurements at $z/h = 1.38$, were found to be enhanced by factors of, on average, 1.3 for momentum flux and 1.9 for sensible heat flux, as compared to the diffusivities calculated using the flux-gradient relationships pertaining to smoother surfaces (Dyer, 1974). But the dependence of the enhancement on the stability was not monotonic (Figure 4).

Monin–Obukhov similarity requires that the dimensionless standard deviations of the vertical velocity and scalar concentrations be functions of $(z - d)/L$. In the surface layer under free convection conditions (large values of $-(z - d)/L$), these functions have the forms

$$\sigma_w/u_* = a_w[-(z - d)/L]^{1/3}\,, \tag{1}$$

$$\sigma_T/T_* = a_T[-(z - d)/L]^{-1/3}\,, \tag{2}$$

$$\sigma_{\rho_v}/\rho_{v*} = a_{\rho_v}[-(z - d)/L]^{-1/3}\,, \tag{3}$$

where σ_w, σ_T and σ_{ρ_v} are the standard deviations of the vertical velocity component, air temperature and water vapour density, respectively, and u_*, T_* and ρ_{v*} are the corresponding characteristic scales defined as

$$u_* = \sqrt{-\overline{u'w'}}\,, \quad T_* = \overline{w'T'}/u_*\,, \qquad \rho_{v*} = \overline{w'\rho_v'}/u_*\,.$$

The values of the constants a_w, a_T and a_{ρ_v} were found to be about 1.9, 0.9 and

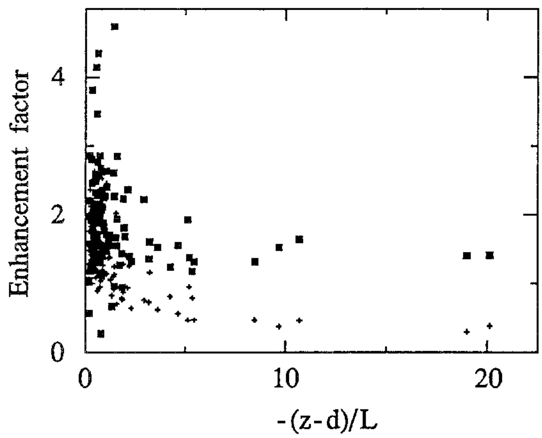

Fig. 4. Enhancement factor (measured eddy diffusivity divided by that predicted with the flux-gradient relationships of Dyer (1974)) calculated from the profile measurements at $z/h = 1.00$ and 1.38 and flux measurements at $z/h = 1.38$ for the Douglas-fir stand at Browns River: (■), sensible heat; (+), momentum. The stability parameter $(z - d)/L$ was calculated from the flux measurements at $z/h = 1.38$.

1.1, respectively, over rather smooth surfaces (Högström and Smedman-Högström, 1974; Takeuchi *et al.*, 1980; Wyngaard *et al.*, 1971; Monji, 1972; Panofsky and Tennekes, 1977; Maitani and Ohtaki, 1987). Ohtaki (1985) found that (1)–(3) performed well in wheat fields.

Figure 5 shows the dimensionless standard deviations as functions of the stability at $z/h = 1.38$. The value of σ_w/u_* at small values of $-(z - d)/L$ was about 1.16, close to 1.25, a typical value for the neutral surface layer (Panofsky and Dutton, 1984). There were large uncertainties in σ_T/T_* and $\sigma_{\rho_v}/\rho_{v*}$ for small values of $-(z - d)/L$. At large values of $-(z - d)/L$, the trend is clear: σ_w/u_* was well approximated by the 1/3 power law, and σ_T/T_* and $\sigma_{\rho_v}/\rho_{v*}$ by the $-1/3$ power law. Overall the measurements and the predictions agree well for large values of $-(z - d)/L$, with slight differences probably caused by the rather arbitrary choice of the value of d.

Shaw *et al.* (1988) observed that the normalized Reynolds stress and turbulence intensity at the middle of a deciduous forest showed clear decreases with the onset of stable conditions from moderately unstable conditions. The ambient conditions during the experiment of the present study were unstable. Stability was found to have little effect on the statistics within the stand.

3.2. Means and Variances of the Velocity Components

Figure 6 shows the profiles of daytime cup wind speed (U) normalized against that at $z/h = 1.38$ and averaged over the nine days listed in Table I, and longitudinal velocity component (u) normalized against that at $z/h = 1.38$. During the experimental period, the 30-min average cup wind speed and the longitudinal

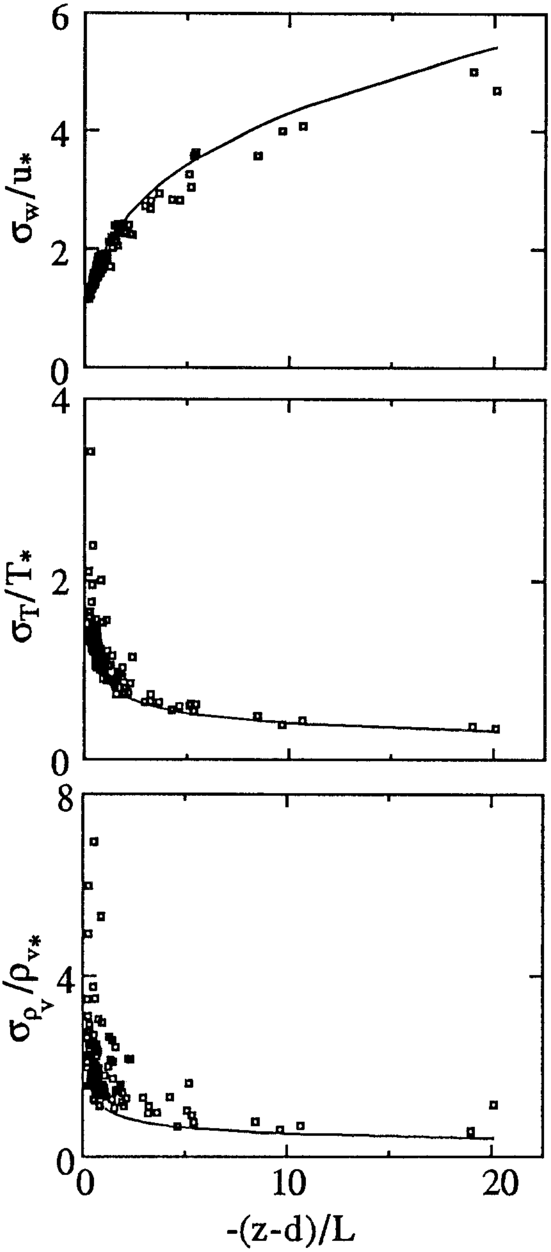

Fig. 5. Dimensionless standard deviations of the vertical velocity component (σ_w/u_*) air temperature (σ_T/T_*) and water vapour density ($\sigma_{\rho_v}/\rho_{v*}$) as functions of the stability parameter $(z - d)/L$ at $z/h = 1.38$ for the Douglas-fir stand at Browns River. Squares: measured; lines: calculated from Equations (1)–(3).

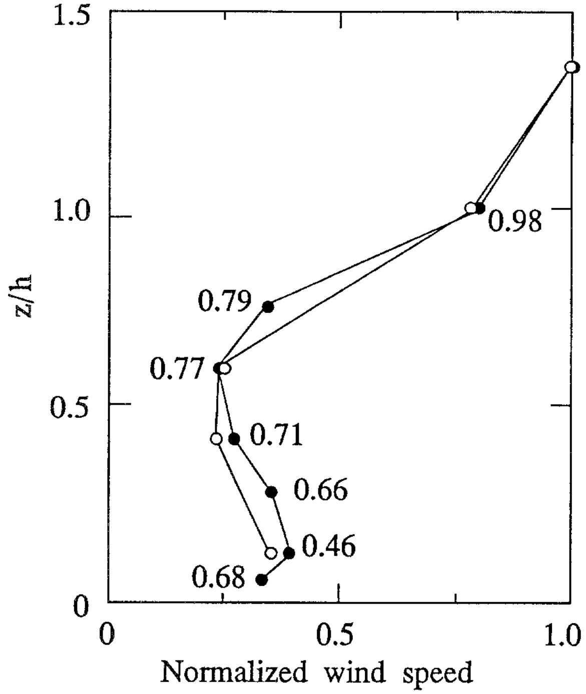

Fig. 6. Profiles of normalized daytime wind speed in the Douglas-fir stand at Browns River: (●), wind speed measured using cup anemometers (U) and averaged over nine days, where the numbers are correlation coefficients (R) between the wind speed at the indicated heights and that at $z/h = 1.38$; (○), longitudinal velocity component (u) measured using one sonic anemometer located for 2–3 days at various heights and normalized against that measured by the other sonic anemometer located permanently at $z/h = 1.38$.

velocity component at $z/h = 1.38$ varied between 0.94 and 3.28 m/s and between 0.22 and 2.60 m/s, respectively. The normalized cup wind speed decreased sharply from $z/h = 1.38$ to $z/h = 0.60$, with a minimum of 0.25 occurring at $z/h = 0.60$. There was a marked secondary maximum at around $z/h = 0.12$, the normalized value being 0.40. The existence of a secondary maximum is a common feature of the wind speed profiles in forest stands having a trunk space relatively free of branches where air movement is less restricted (e.g., Allen, 1968; Shaw, 1977; Baldocchi and Hutchison, 1987; Baldocchi and Meyers, 1988). The correlation coefficient between the cup wind speed at the height of the secondary maximum and that at $z/h = 1.38$ was lower than those between the wind speed at all other heights and that at $z/h = 1.38$ (Figure 6). This indicates that the wind at the height of the secondary maximum was least coupled to that above the stand compared to the wind at the other heights. The profile of the normalized longitudinal velocity component was similar to the profile of the normalized cup wind speed.

In the following plots of the vertical profiles of statistics in this paper, values at $z/h = 1.38$ were averaged over 31 July and 1 August, while those at lower heights

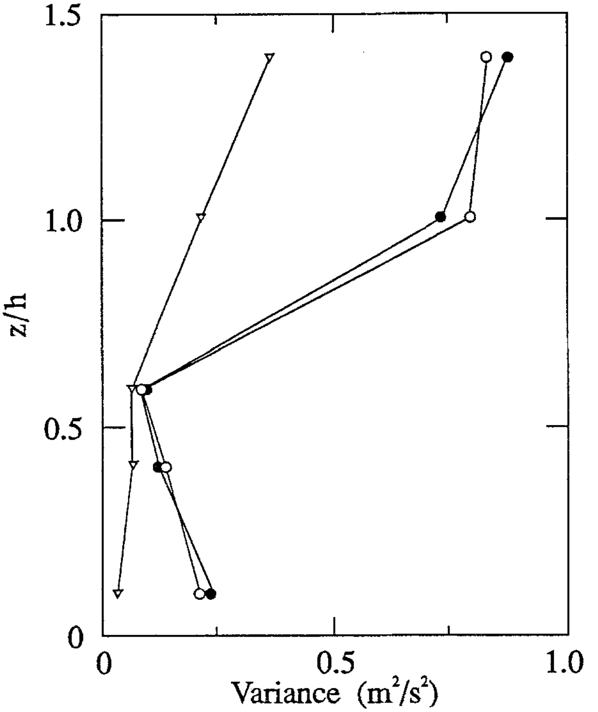

Fig. 7. Profiles of daytime average velocity variance in the Douglas-fir stand at Browns River: (○), longitudinal component ($\overline{u'^2}$); (●), lateral component ($\overline{v'^2}$); (▽), vertical component ($\overline{w'^2}$). The average values of the standard error of mean (SEM) for $\overline{u'^2}$ and $\overline{v'^2}$ were 0.08 m^2/s^2 on the top and above the stand and 0.01 m^2/s^2 within the stand, and the corresponding values for $\overline{w'^2}$ were 0.02 and 0.01 m^2/s^2.

were averaged over the corresponding operating periods (Table I). The plots of these ensemble averages should retain the basic features of these statistics as functions of height because the atmospheric conditions were similar throughout the experimental period.

Figure 7 illustrates the dependence of the velocity variance on height. The variance of the vertical velocity component was smaller than the variances of the longitudinal and lateral components, a feature in agreement with the observations made in agricultural crops by Shaw *et al.* (1974), Finnigan (1979a) and Wilson *et al.* (1982), and in forests by Baldocchi and Hutchison (1987), Baldocchi and Meyers (1988), Shaw *et al.* (1988) and Amiro (1990a), and decreased approximately linearly with decreasing height. But unlike most of the experimental results of those workers who showed that $\overline{u'^2}$ was larger than $\overline{v'^2}$, the profiles of $\overline{u'^2}$ and $\overline{u'^2}$ in the present study were quite similar both in magnitude and in shape. Both variances were relatively constant with height in the layer extending a few metres above the stand and decreased rapidly with depth into the stand. Both reached

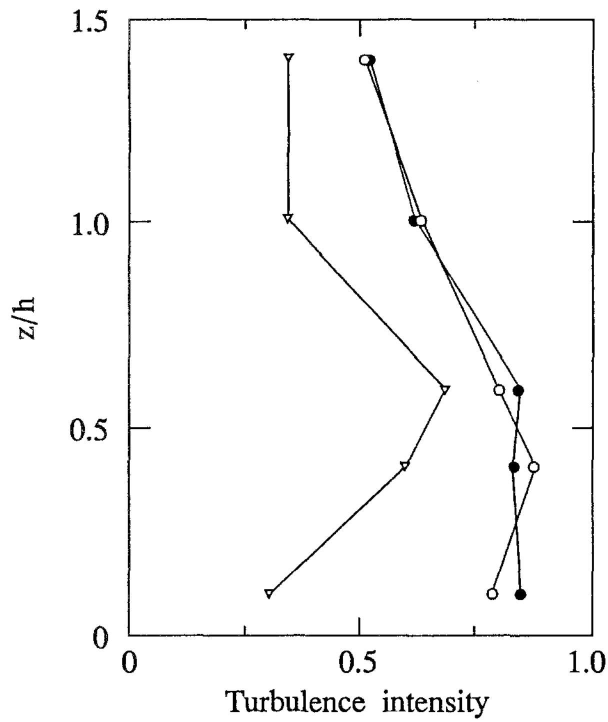

Fig. 8. Profiles of daytime average turbulence intensity in the Douglas-fir stand at Browns River: (○), longitudinal component (i_u); (●), lateral component (i_v); (▽), vertical component (i_w). The average values of SEM were 0.04 for i_u and i_v and 0.02 for i_w.

minima at $z/h = 0.60$, where their values were about equal to the value of $\overline{w'^2}$. Below this height, both increased slightly with depth.

Figure 8 shows the vertical profiles of turbulence intensity (velocity standard deviation divided by the average longitudinal velocity component) for the three velocity components: longitudinal (i_u), lateral (i_v) and vertical (i_w). These profiles reflect the combined effect of the variance (Figure 7) and the longitudinal velocity component (Figure 6) profiles. On average, at $z/h = 1.38$, i_u and i_v had a value of 0.52. They increased gradually in magnitude with decreasing height. At $z/h = 0.12$, the values of i_u and i_v were 0.80 and 0.86, respectively. The profiles of i_u and i_v reported here were similar in shape and magnitude to that for the u component observed in a Japanese larch plantation (Allen, 1968), but differed from those observed in a spruce forest by Amiro (1990a) and in a deciduous forest by Baldocchi and Meyers (1988) in that their profiles of i_u and i_v showed marked maxima in the middle of the canopy.

The turbulence intensity of the vertical velocity component, i_w was approximately constant at 0.34 in the layer $1.00 < z/h < 1.38$. It increased sharply with depth into the canopy. A maximum value of 0.68 occurred at $z/h = 0.60$, where the wind speed was lowest (Figure 6). Below this height, the intensity decreased with decreasing height. The value of i_w near the forest floor ($z/h = 0.12$) was about 0.30. A well-defined maximum in the i_w profile seems to be a common phenomenon occurring in the layer between the middle and upper third of forest stands (Amiro and Davies, 1988; Baldocchi and Meyers, 1988; Shaw *et al.*, 1988; Bradley *et al.* reported in Wilson *et al.* (1982); Amiro, 1990a). In most cases, the maximum value of i_w is between 0.6 and 0.8.

3.3. Higher Order Moments

The profiles of velocity skewness are presented in Figure 9. The average values of the skewness for the three velocity components at $z/h = 1.38$ were close to zero, the value for a Gaussian distribution. The values of Sk_u and Sk_v increased linearly with decreasing height until they reached maximum values of 0.73 and 0.57, respectively, at the middle of the canopy ($z/h = 0.60$), where the wind speed was lowest (Figure 6). Below this height, both Sk_u and Sk_v decreased with decreasing height. Positive values of Sk_u were consistent with the theoretical arguments of Shaw and Seginer (1987) that the penetration of occasional sweeps of fast moving air into the canopy from above should result in positive Sk_u. However, they did not expect the nonzero Sk_v reported here.

Intense turbulent activity above a vegetation canopy is carried downward whereas in the interior of the canopy there is no source for the creation of large updrafts (Shaw and Seginer, 1987). Consequently, the vertical velocity component immediately above the stand and in the canopy layer was negatively skewed. The most negative value of -0.52 for Sk_w occurred at the middle of the canopy ($z/h = 0.60$). The profile of Sk_w was practically a mirror image of the profiles of Sk_u and Sk_v, a pattern observed previously in several other experimental studies (Seginer *et al.*, 1976; Raupach *et al.*,1986; Shaw and Seginer, 1987; Amiro, 1990a).

As shown in Figure 10, the kurtosis values for the three velocity components above the stand in this study were not significantly different from 3, the value for a Gaussian distribution. Higher values were observed in the canopy layer, indicating the existence of active extreme events in this layer. Like that of skewness, the magnitude of kurtosis peaked at $z/h = 0.60$. The peak values for Kr_u, Kr_v, Kr_w were 5.1, 5.1 and 4.1, respectively. Kurtosis was smaller in the trunk space, the values at $z/h = 0.12$ being 3.2, 2.9 and 3.9, respectively. This might indicate that the canopy layer above suppressed the activity of extreme events by blocking the penetration of large gusts from above the stand and imposing a thermal inversion (Lee, 1992) on the trunk flow.

3.4. Reynolds Stress

The variation of Reynolds stress with height is presented in Figure 11. The ratio, $u_*/\bar{u}$, at $z/h = 1.38$ was 0.20 ± 0.08. A reduction of 20% in the stress occurred from the tree tops to $z/h = 1.38$. The stress decreased sharply with depth into the canopy due to momentum absorption by the foliage. It was negative at the base

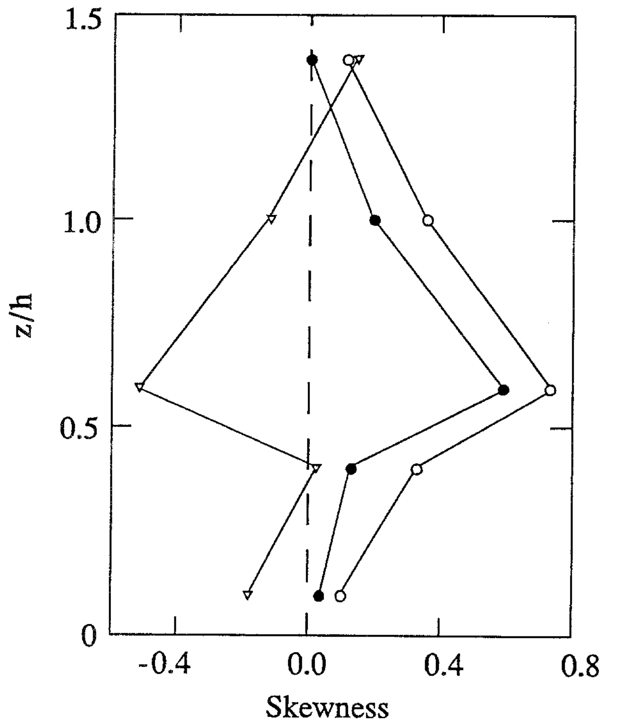

Fig. 9. Profiles of daytime average velocity skewness in the Douglas-fir stand at Browns River: (○), longitudinal component (Sk_u); (●), lateral component (Sk_v); (▽), vertical component (Sk_w). The average values of SEM were 0.06 for Sk_u and Sk_v and 0.04 for Sk_w.

of the canopy ($z/h = 0.42$) and in the middle of the trunk space ($z/h = 0.12$), with magnitudes of about 25% of that at $z/h = 1.38$.

Negative Reynolds stress persistently occurred at $z/h = 0.12$ and 0.42, with only two exceptions in a total of seventy-one 30-min runs. The most negative values were $-0.052\,\mathrm{m^2/s^2}$ at $z/h = 0.12$ and $-0.058\,\mathrm{m^2/s^2}$ at z/h = 0.42. An explanation for the negative values can be obtained by examining the Reynolds stress budget (Raupach *et al.*, 1986)

$$\frac{\partial}{\partial t}\langle\overline{u'w'}\rangle = 0 = \underbrace{-\langle\overline{w'^2}\rangle\frac{\partial\bar{u}}{\partial z}}_{P_s} \underbrace{- \left\langle \overline{u_1'u_j'}''\,\frac{\partial\overline{u_3}''}{\partial x_j} + \overline{u_3'u_j'}''\,\frac{\partial\overline{u_1}''}{\partial x_j}\right\rangle}_{P_w}$$

$$\underbrace{-\frac{\partial}{\partial z}\langle\overline{u'w'^2}\rangle}_{T_t} + \underbrace{\frac{1}{\rho}\left\langle\overline{p'\left(\frac{\partial u'}{\partial z} + \frac{\partial w'}{\partial x}\right)}\right\rangle}_{\Phi}, \tag{4}$$

where u_i and x_i ($i = 1, 2, 3$) are the components of velocity and position vectors, respectively, in tensor notation, (u, v, w) and (x, y, z) are velocity and position

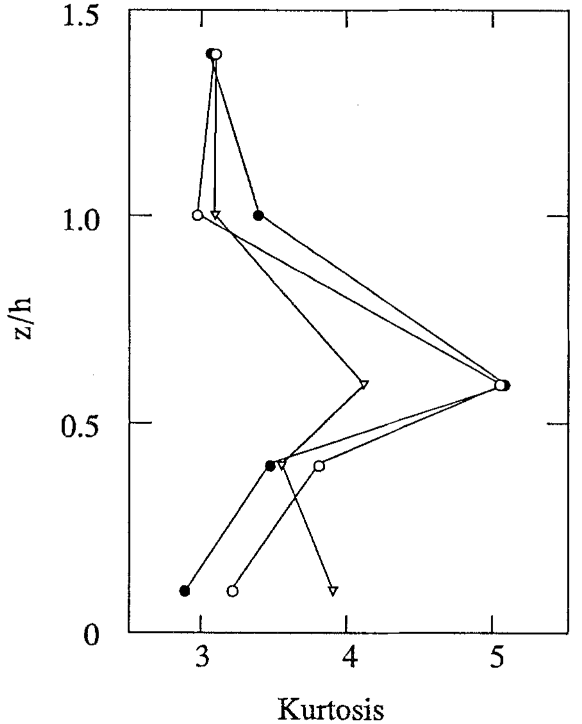

Fig. 10. Profiles of daytime average velocity kurtosis in the Douglas-fir stand at Browns River: (○), longitudinal component (Kr_u); (●), lateral component (Kr_v); (▽), vertical component (Kr_w). The average values of SEM were 0.13 for Kr_u and Kr_v and 0.10 for Kr_w.

vectors in meteorological notation, t is time, p is pressure, ρ is air density; triangular brackets and double primes denote, respectively, spatial averages (horizontally) and departures therefrom; and overbar and single prime denote, respectively, temporal averages and departures therefrom. On the RHS of (4), P_s and P_w are shear production and wake production, respectively, representing local interactions, T_t is turbulent transport, representing interactions between layers, and Φ is the interaction between velocity and pressure fields. We omit small terms such as dispersive flux divergence, molecular flux divergence, molecular dissipation and pressure transport, according to the studies of Shaw (1977) and Raupach *et al.* (1986).

It is not feasible to estimate the magnitudes of the individual terms of (4) in the stand of the present study, but qualitative conclusions can be drawn from (4). By parameterizing Φ as (Wilson and Shaw, 1977; Wyngaard, 1981)

$$\Phi = -\langle \overline{u'w'} \rangle / \tau ,$$

where τ is a time scale, (4) becomes

$$\langle \overline{u'w'} \rangle / \tau = P_s + P_w + T_t . \tag{5}$$

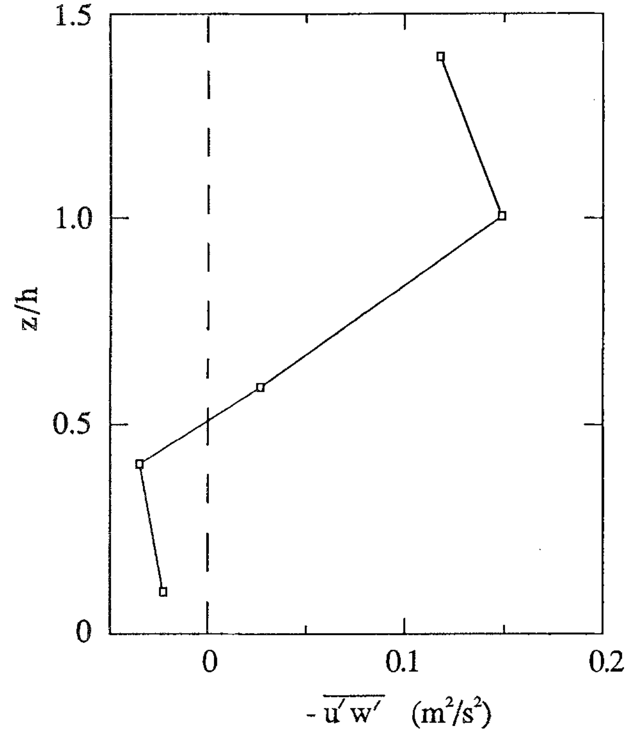

Fig. 11. Profile of daytime average kinematic Reynolds stress in the Douglas-fir stand at Browns River. The average values of SEM were 0.014 m^2/s^2 on the top and above the stand and 0.002 m^2/s^2 within the stand.

According to (5), the contribution of P_s to Reynolds stress $-\langle\overline{u'w'}\rangle$ was positive above $z/h = 0.60$ due to the positive wind speed gradient (Figure 6) and negative in the layer between $z/h = 0.12$ and 0.60 due to the negative wind speed gradient. Raupach *et al.* (1986) have shown, by manipulating the budget equation of $\langle\bar{u}''\bar{w}''\rangle$ (Raupach and Shaw, 1982), that P_w can be neglected provided that: (1) there is negligible direct dissipation of mean kinematic energy into heat by the canopy, and (2), the dispersive covariance and dispersive transport are both negligible. If non-zero dispersive covariances exist, a little manipulation of this budget equation yields (Lee, 1992)

$$P_w = \langle\bar{w}''\bar{w}''\rangle\frac{\partial\langle\bar{u}\rangle}{\partial z}\,. \tag{6}$$

Equation (6) means that P_w, if not zero, acts in a similar way as P_s in that both have the same sign and that both are linear with the local wind speed gradient, $\partial\langle\bar{u}\rangle/\partial z$. T_t is largely driven by the gradient of Reynolds stress (Shaw, 1977). To assess its relative importance, the second-order closure model of Wilson and Shaw (1977) was applied to the flow within the stand. The simulated results suggested that the magnitude of T_t in the trunk space was on average 1/3 of that of P_s. The dominant role of P_s was a result of the very negative wind speed gradient and gave rise to the negative values of Reynolds stress at $z/h = 0.12$ and 0.42. In fact, Reynolds stress was found to have strong dependence on the wind speed gradient at the lower levels, the correlation coefficient being 0.70 at $z/h = 0.12$ for thirty-seven 30-min runs and 0.83 at $z/h = 0.42$ for twenty-eight 30-min runs.

It should be pointed out that, although the non-local interactions represented by T_t are likely to be small compared to the local interactions represented by P_s and P_w for the Reynolds stress budget at lower heights of a plant canopy, they are generally significant for the flux budgets of scalars such as sensible heat and water vapour. This is well demonstrated by the phenomenon of counter-gradient flux frequently observed in the lower parts of forest stands (Denmead and Bradley, 1985; Amiro, 1990a, Leclerc, 1987; II). A comparison of the Reynolds stress budget (Raupach *et al.*,1986) and the heat flux budget (Coppin *et al.*,1986) in an artificial canopy in a wind tunnel shows that, while T_t is much smaller in magnitude than P_s in the Reynolds stress budget, T_t is equal in magnitude to P_s in the heat flux budget.

Negative Reynolds stress, that is, an upward flux of momentum has been observed at the lower heights in vegetation canopies on a few other occasions (Raupach *et al.*, 1986; Baldocchi and Hutchison, 1987, Maitani and Shaw, 1990; Lee and Black, 1992). The momentum conservation equation can be examined to shed some light on the origin of the upward momentum flux. For a stationary flow without buoyancy forces and advection, the conservation equation for momentum is

$$\frac{\partial}{\partial z}\langle -\overline{u'w'}\rangle + \frac{\partial}{\partial z}\langle \overline{u}''\overline{w}''\rangle = C_d A \langle \bar{u}\rangle^2 + \frac{1}{\rho}\frac{\partial \langle \bar{p}\rangle}{\partial x}\,, \tag{7}$$

where C_d is the effective drag coefficient of the plant elements and A is the element area density (Raupach *et al.*, 1986). Integration of (7) with respect to z yields

$$\begin{aligned}[\langle -\overline{u'w'}\rangle + \langle -\overline{u}''\overline{w}''\rangle\rangle]_z &= \int_0^z C_d A\langle \bar{u}\rangle^2\,\mathrm{d}z \\ &+ [\langle -\overline{u'w'}\rangle + \langle -\overline{u}''\overline{w}''\rangle]_0 + \int_0^z \frac{1}{\rho}\frac{\partial\langle \bar{p}\rangle}{\partial x}\,\mathrm{d}z\,. \end{aligned}\tag{8}$$

The first and second parts of the term on the LHS of (8) are spatially averaged Reynolds momentum flux (or Reynolds stress, assumed to equal the point measurement (Shaw, 1985)) and dispersive momentum flux (or dispersive stress), respectively; the first term on the RHS of (8) represents momentum absorption by the plant elements, the second term momentum absorption by the ground surface, and the third term the contribution of momentum divergence due to the longitudinal pressure gradient, $\partial\langle\bar{p}\rangle/\partial x$. The onset of the sea/upslope breeze in the daytime was associated with a negative $\partial\langle\bar{p}\rangle/\partial x$. According to the estimates of Atkinson (1981, pp. 125–127 and 217–219), the gradient due to the uneven radiative heating between land and sea was on the order of 0.2 kPa/100 km, and the gradient due to the uneven radiation heating between slope and horizontal land was on the same order of magnitude. Using a value of −0.5 kPa/100 km for $\partial\langle\bar{p}\rangle/\partial x$, the third term on the RHS of (8) was estimated at $-0.035\ \mathrm{m^2/s^2}$ for $z/h = 0.42$. Momentum absorption by the ground was probably negligible. Momentum absorption by the trunks (the dominant elements below $z/h = 0.42$) was estimated at $0.010\ \mathrm{m^2/s^2}$ for the height $z/h = 0.42$, by using the value of C_d for a cylinder in turbulent flow (0.45, p. 622, Schlichting, 1968). The sum of the terms on the RHS of (8) was thus on the order of $-0.025\ \mathrm{m^2/s^2}$, which was similar to the average value of $-0.033\ \mathrm{m^2/s^2}$ for $\langle -\overline{u'w'}\rangle$ measured at $z/h = 0.42$. The result of this simple exercise suggests that the longitudinal pressure gradient might, to a large extent, be responsible for the upward momentum flux. (Apparently, this pressure gradient would also contribute to the reduction of Reynolds stress from $z/h = 1.00$ to 1.38.) It is not feasible to estimate the magnitude of the dispersive term from a point measurement, but results of earlier wind tunnel experiments suggested that this term might be negligible (Raupach *et al.*, 1986; Mulhearn, 1978).

3.5. Quadrant Representation of Reynolds Stress

Quadrant-hole analysis, a conditional-sampling technique, is useful in identifying kinds of turbulent motion which dominate the vertical transfer of momentum represented by the kinematic Reynolds stress, $-\overline{u'w'}$. It was used in the experimental investigations of momentum transfer in agricultural crops (Finnigan, 1979b; Shaw *et al.*, 1983), in an almond orchard (Baldocchi and Hutchison, 1987), in deciduous forests (Baldocchi and Meyers, 1988; Gao *et al.*, 1989; Maitani and Shaw, 1990), and in a wind tunnel model canopy (Raupach *et al.*, 1986). These studies have shown that within a vegetation canopy, a large proportion of momentum transfer occurs in a small fraction of time and that in the upper part of and immediately above the canopy, the transfer is dominated by sweeps or gusts.

The four quadrants in the $u'w'$ plane are conventionally labelled as outward interaction ($i = 1$; $u' > 0$, $w' > 0$), ejection ($i = 2$; $u' < 0$, $w' > 0$), inward interaction ($i = 3$; $u' < 0$, $w' < 0$), and sweep ($i = 4$; $u' > 0$, $w' < 0$). A stress fraction $S_{i,H}$ and a time fraction $t_{i,H}$ are defined, respectively, as

$$S_{i,H} = \frac{1}{|\overline{u'w'}|}\frac{1}{T}\int_0^T u'(t)w'(t)I_{i,H}\,\mathrm{d}t\,,$$

$$t_{i,H} = \frac{1}{T}\int_0^T I_{i,H}\,\mathrm{d}t\,,$$

where T is the averaging time interval (30 min in this study), and $I_{i,H}$ is a conditioning function which equals one if the point $(u'(t), w'(t))$ is located in the ith

TABLE II

Values of Reynolds stress $-\overline{u'w'}$, standard deviations of the longitudinal and vertical velocity components (σ_u and σ_w), and the mean longitudinal velocity component ($\bar{u}$) at the indicated levels for the five runs selected for quadrant-hole analysis of Reynolds stress for the Douglas-fir stand at Browns River. The stability parameter $(z-d)/L$ was calculated from the measurements at $z/h = 1.38$

Time interval PST	z/h	$(z-d)/L$	$-\overline{u'w'}$ m^2/s^2	σ_u m/s	σ_w m/s	$\bar{u}$ m/s
13:30–14:00 19 July	0.12	−0.26	−0.024	0.45	0.19	1.00
12:00–12:30 27 July	0.42	−0.25	−0.052	0.41	0.32	0.42
12:30–13:00 30 July	0.60	−0.35	0.036	0.34	0.33	0.50
13:30–14:00 1 Aug	1.00	−0.25	0.184	1.17	0.54	2.14
12:00–12:30 27 July	1.38	−0.25	0.354	1.16	0.75	2.19

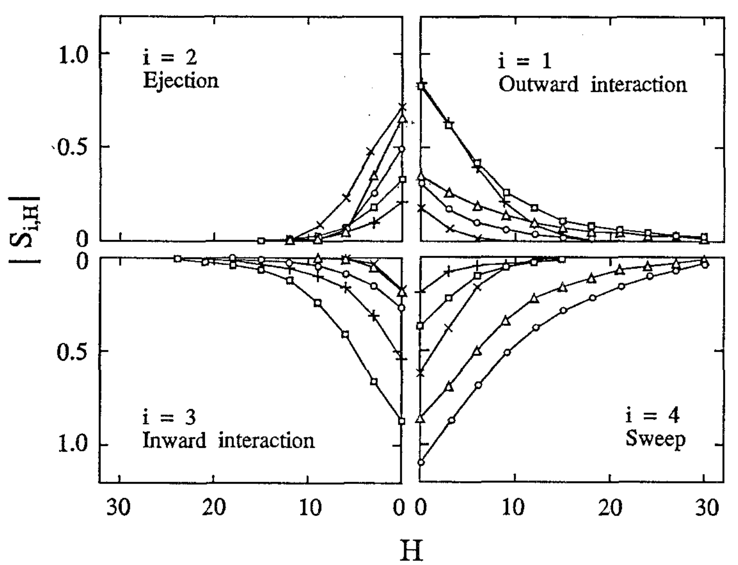

Fig. 12. Stress fraction ($S_{i,H}$) plotted against hole size (H) for the Douglas-fir stand at Browns River for five values of z/h: 1.38 (×), 1.00 (△), 0.60 (○), 0.42 (+), and 0.12 (□).

quadrant and $|u'(t)w'(t)|$ is greater than $H|\overline{u'w'}|$ and zero otherwise. The dimensionless parameter, H, is called hole size.

One 30-min run at each level was selected for quadrant-hole analysis (Table II). As shown in Table II, the stability parameter, $(z-d)/L$, was similar for all runs. Figure 12 shows the stress fraction $S_{i,H}$ plotted against hole size H and Table III

TABLE III

Intermittency parameters (H' and $\Sigma_{i=1}^{4} t_{i,H'}$), exuberance ($(S_{1,0} + S_{3,0})/(S_{2,0} + S_{4,0})$) and ratio of the contribution to Reynolds stress by sweeps to that by ejections ($S_{4,0}/S_{2,0}$) for the Douglas-fir stand at Browns River

z/h	0.12	0.42	0.60	1.00	1.38
H'	8.0	5.6	7.5	4.8	5.0
$\Sigma_{i=1}^{4} t_{i,H'}$	0.064	0.084	0.064	0.125	0.096
$\frac{S_{1,0} + S_{3,0}}{S_{2,0} + S_{4,0}}$	−2.44	−3.45	−0.36	−0.39	−0.26
$\frac{S_{4,0}}{S_{2,0}}$	1.12	0.90	2.20	1.30	0.86

lists related information. In Table III, H' is the hole size above which half of the momentum transfer occurs

$$\left|\sum_{i=1}^{4} S_{i,H'}\right| = 0.5$$

and $\Sigma_{i=1}^{4} t_{i,H'}$ is the corresponding time fraction. $\Sigma_{i=1}^{4} t_{i,H'}$ and H' are measures of intermittency. The intermittent nature of the momentum transfer can be readily seen. At all levels, half of the momentum flux was contributed by the events with hole size greater than 4.8–8.0, which occupied small fractions of time (6.4–12.5%).

The relative importance of the kinds of turbulent motion in momentum transfer can be examined by forming ratios of stress fractions at zero hole size. The ratio of the contributions by the interaction components ($S_{1,0} + S_{3,0}$) to the contributions by the ejection and sweep components ($S_{2,0} + S_{4,0}$), called exuberance (Shaw *et al.*, 1983), varied between −0.26 and −0.39 in the layer between $z/h = 0.60$ and 1.38, which is consistent with the net downward momentum flux. At $z/h = 1.38$, ejections dominated over sweeps, the ratio $S_{4,0}/S_{2,0}$ being 0.86. But sweeps gained strength at the tree tops and in the canopy layer. The values of the ratio $S_{4,0}/S_{2,0}$ were 1.3 at $z/h = 1.00$ and 2.2 at $z/h = 0.60$. The dominance of sweeps over ejections was even greater at these two heights if only larger events were considered, as shown in Figure 12. These results generally agree with those of the experimental studies reviewed previously, but differ in some details. For example, the magnitudes of $S_{i,0}$ (i = 1–4) in the present work were generally less than 1, while Baldocchi and Meyers (1988) reported the magnitudes to be 1 to 3 for a deciduous forest.

At the lower heights of the stand, a different picture evolved. The interaction components played a major role in momentum transfer. The exuberance values were −2.44 at $z/h = 0.12$ and −3.45 at $z/h = 0.42$. This is consistent with the upward transfer of momentum or negative Reynolds stress at these two heights as discussed in the previous section. Baldocchi and Hutchison (1987) attributed the large contribution of the interaction components to either sloshing of the air near the forest floor or the existence of a systematic wake circulation in the lee of the tree upwind. However, it likely reflects a local interaction with wind speed gradient. A downward/upward motion (negative/positive w') would normally result in a decrease/increase in u (negative/positive u') due to the negative wind speed gradient in the layer between $z/h = 0.12$ and 0.42.

4. Summary and Conclusions

Daytime turbulence statistics for the velocity field within and above a Douglas-fir forest on a 5° slope have been presented. The stability parameter, $(z - d)/L$ varied mainly between -0.20 and -5.0 at $z/h = 1.38$. Eddy diffusivities under these moderately to strongly unstable conditions, calculated from the profile measurements at $z/h = 1.00$ and 1.38 and the flux measurements at $z/h = 1.38$, were found to be enhanced by factors of, on average, 1.3 for momentum flux and 1.9 for sensible heat flux, as compared to the diffusivities calculated using the flux-gradient relationships pertaining to smoother surfaces. However, the similarity functions for the standard deviations of the vertical velocity component, air temperature and water vapour density were found to perform well at $z/h = 1.38$.

The vertical profiles of the turbulence statistics reflect the influence of the vertical structure of the stand. A marked secondary maximum in the wind speed profile occurred in the middle of the trunk space (around $z/h = 0.12$). The turbulence intensities for the longitudinal and lateral velocity components increased with decreasing height, but the intensity for the vertical velocity component had a maximum at $z/h = 0.60$, where the leaf area density was highest. Magnitudes of the higher order moments (skewness and kurtosis) for the three velocity components were higher in the canopy layer than in the trunk space and above the stand.

There was a 20% reduction in Reynolds stress from $z/h = 1.00$ to 1.38, probably a result of topographic effects and land–sea/upslope–downslope circulations. Negative Reynolds stress persistently occurred at $z/h = 0.12$ and 0.42 (height of the base of the canopy). Examination of the Reynolds stress budget revealed that the negative value was associated with negative wind speed gradients at the two heights. The longitudinal pressure gradient due to the land–sea/upslope–downslope circulations was believed to be the main factor responsible for the upward momentum flux or negative Reynolds stress.

Momentum transfer was highly intermittent. Sweep and ejection events dominated the transfer process at $z/h = 0.60$, 1.00 and 1.38, with sweeps playing the more important role of the two at $z/h = 0.60$ and 1.00 and the less important role at $z/h = 1.38$. But interaction events were of greater magnitude than sweep and ejection events at $z/h = 0.12$ and 0.42.

There are several areas for further work. First, night-time regimes are yet to be investigated. A preliminary examination of the wind profiles in this stand at night revealed some distinct features, which deserve further study. Second, multipoint measurements along a horizontal transect are needed for assessing the relative importance of dispersive stress in forests. Third, because of the tallness of forests, the role of the horizontal pressure gradient due to meso-scale and (to a less extent) synoptic-scale circulations in affecting the canopy flow should not be overlooked. It is believed that the predictions of canopy flow models can be improved by including this pressure gradient effect.

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