Turbulent exchange processes within and above a straw mulch.  
Part I: Mean wind speed and turbulent statistics

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Abstract

Mulching is a technique widely used to conserve soil and moderate its microclimate. Modelling transfer processes in mulches is limited by our lack of understanding of turbulent exchange within the mulch. This paper, the first of a two-part series, reports on measurements of wind and turbulence made above and within a 10 t ha−1 barley-straw mulch using custom-made hot-wires and a tri-axial hot-film probe. Wind regimes within the mulch during daytime (relatively high wind) and nighttime (low wind) differ greatly. During daytime, 10 min average horizontal wind speeds at all levels in the mulch (where they vary nearly exponentially with height) correlate well with (near-logarithmic profile) wind speeds above the mulch and are not affected by the strong temperature inversion existing in the mulch. During nighttime, 10 min average horizontal wind speeds within the mulch are decoupled from (poorly correlated with) wind speeds in the generally stable air above the mulch. Unstable conditions in the mulch at night lead to free convection, which explains the good correlation of 10 min average wind speeds at all heights within the mulch and the high evaporation rates we measured below the mulch. Under high wind conditions most of the drag occurs very near the top of the mulch which behaves as an aerodynamically smooth surface similar to a bare soil. Turbulence within the mulch is of high intensity and is dominated by intermittent gusts, with the extreme values described by a Gumbel distribution. The frequency of the gusts agrees reasonably well with that found for laboratory mixing layers. The wind and turbulence regimes in the mulch resemble in many ways those in plant canopies much larger in height and lower in leaf area density. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Mulching, which maintains the soil surface covered with plant residues between successive crops or when vegetation cover is incomplete, is widely adopted in agriculture, forestry and horticulture (Stigter, 1984; Unger, 1994). Advantages of mulching include limiting soil erosion by wind and runoff, reducing water loss by evaporation, changing soil temperature favourably, and enhancing soil structure (Unger, 1994). Many previous studies have used empirical models to describe the effects of mulch properties on the thermal and moisture regimes of the underlying soil and on crop yields (Phipps and Cochrane, 1975; Gupta et al., 1981; Steiner, 1989). It is doubtful, however, that universal relationships can be obtained in this way. The empirical approach requires a large amount of field work to accommodate the complex way in
which the atmosphere, mulch, and soil interact. Recently, more promising simulation models have been developed that incorporate basic mass and energy exchange processes occurring in soil–mulch–atmosphere systems (Bristow et al., 1986; Hares and Novak, 1992; Bussière and Cellier, 1994). These researchers successfully modelled exchange processes in the soil and atmosphere layers but found it difficult to correctly simulate processes within the mulch.

The most important cause of this difficulty is that mass and energy exchange processes in a mulch involve not only molecular diffusion but also turbulent transfer (Kimball and Lemon, 1971; Campbell et al., 1980; Tanner and Shen, 1990). In these studies heat and mass transfer rates increased linearly with increasing wind speed measured above the surfaces. Classical flux–gradient relationships ($K$-theory) have been used in various forms to simulate turbulent exchange processes within a mulch. Bussière and Cellier (1994) divided a sugar-cane mulch into many layers and assumed that the diffusivities increase exponentially with height within it. Their simulation predicted that the evaporation rate beneath the sugar-cane mulch was ‘weak’ but their measured fluxes were large, 150–200 W m$^{-2}$. Similar discrepancies were also found between predicted and measured sensible heat fluxes above the mulch, with the former being about half the latter for two clear days. The failure of their simulation was perhaps not unexpected since $K$-theory is now widely accepted as unsuitable for canopy flows (Raupach, 1989). Higher-order closure schemes (Meyers and Paw U, 1987) and Lagrangian models (Raupach, 1989) have been developed to improve the description of transfer within canopies beyond the simplest formulations of $K$-theory.

To evaluate the usefulness of these alternative models for a mulch, measurements of turbulence and turbulent fluxes within a mulch must be made. Because mulches are generally only a few cm high and very dense, with residue area density ranging up to about 100 m$^2$ m$^{-3}$, fluxes cannot easily be measured with standard micrometeorological techniques such as eddy correlation. To circumvent this, we developed several new methods to measure sensible heat (Chen et al., 1997b), latent heat (Chen and Novak, 1997), and radiative fluxes (Novak et al., 2000b) within and above straw mulches. In this series of two papers we characterize the regimes of turbulence and turbulent fluxes within and above a barley-straw mulch. The second paper concentrates on turbulent fluxes of sensible and latent heat (Novak et al., 2000a), while this paper describes the wind regimes, including mean wind speed profile relationships and turbulent statistics.

2. Field measurements and data analysis

2.1. Experimental period and site

Micrometeorological field experiments were conducted at the University of British Columbia Plant Science Research Station, Vancouver, Canada, from July to October for three consecutive years (1992–1994). Data used in this paper are from a 3-day period in 23–25 August 1994, except where indicated otherwise. This period was chosen because during it wind speeds were measured simultaneously both within and above the canopy, it contained a wide variety of wind regimes typical of our study, and it included 25 August, when high-frequency wind component fluctuations were measured. The weather on these days was rain-free with mostly clear skies.

The site, a 25 m by 40 m area, was surrounded by short crops and bare areas. The dominant wind direction during the study was west to northwest (W–NW). For all three seasons, a circular area of either 10 m (1992) or 14 m (1993 and 1994) diameter in the southeast corner of the site was successively covered manually for about 5–10 days with barley straw at rates of 2, 5, 10, and 15 t ha$^{-1}$ (resulting in mean heights, $h$, of 1.2, 3.0, 6.6, and 9.0 cm, respectively) while the surrounding area remained bare. Due to qualitative similarities in the results for different application rates, only measurements from the 10 t ha$^{-1}$ mulch are reported. All measurements within and above the mulch were made at locations within 3 m of each other near the centre of the plot. A typical piece of the barley straw had a length of about 30 cm, a width of 0.3–0.5 cm, and a thickness of 0.1–0.3 cm. The pieces were predominantly oriented horizontally. The total projected element area per unit mass of the mulch was 5.6 m$^2$ kg$^{-1}$, as measured with a video camera and image analysis software (Leaf Area and Analysis Programme, Skye Instruments Ltd., Llandrindod Wells, Powys, UK), with resulting total projected residue area...
density approximately equal to 85 m$^2$ m$^{-3}$. Because the residue consisted mostly of flat pieces, the total projected area is nearly equal to the total one-sided area.

2.2. Mean ‘cup’ wind speed

The mean magnitude of the horizontal wind speed, or cup wind speed, was measured within and above the mulch with miniature custom-made hot-wire anemometers (Orchansky et al., 1994), designated hereafter as HWs. The HW is a modified version of an anemometer developed by Kanemasu and Tanner (1968). It consists of a 2 mm long, 0.8 mm diameter ceramic rod with a heating wire and a constantan/chromel thermocouple junction inserted into two 0.127 mm diameter longitudinal holes in the rod. The thermocouple junction is connected to another junction suspended in the air about 20 mm from the ceramic rod and centred between two 0.3 mm diameter stainless steel posts that support the rod in the vertical position. Thin plastic discs 1.5 cm in diameter were mounted horizontally just outside each support post above and below the rod to minimize the effects of the wind component along the axis of the ceramic rod. Calibration was performed for horizontal wind speed in the range 0.035–0.3 m s$^{-1}$ by mounting the HW facing tangentially at 0.5 m radius on a mechanical turntable operated at various constant angular rotation rates. The relationship between horizontal wind speed and the inverse of the voltage difference between the two thermocouple junctions, proportional to the temperature difference, was linear in this wind speed range. Calibration for higher wind speed (in the range 0.7–2 m s$^{-1}$) was performed in the U.B.C. Department of Mechanical Engineering wind tunnel against wind speed calculated from a Pitot tube and manometer system. A different linear equation was used for wind speed in this range. The response time of the HW is $\sim$1 s, which is too long to measure critical turbulent statistics within and above the mulch.

In the field, each HW was operated with the support posts aligned in the W–NW direction. They were mounted on a vertical rod, 1.3 cm in diameter, located about 30 cm downwind of the HW sensor. It was assumed that the HW measured mean cup wind speed, $\bar{v} = (u^2 + v^2)^{1/2}$, where $u$ and $v$ are the longitudinal and lateral wind components, respectively, and the overbar stands for a time average. Four HWs were operated simultaneously at various heights within and above the mulch with time-averaging of $s$, sampled every 10 (1993) or 20 s (1994), done on-line every 5 (1993) or 10 min (1994). At least 3 days of data were obtained at each of the following heights above ground in 1993 and 1994: $z$=1.1, 3.3, 6.6, 7.6, 8.6, 9.6, 10.6, 11.1, 11.6, 12.6, and 13.6 cm. The HWs were at $z$=1.1, 3.3, 6.6, and 9.6 cm during 23–25 August 1994.

The 10 min average magnitude of $s$ was also measured at $z$=24 and 57 cm throughout the experiment using cup anemometers (model 901-LED, C.W. Thonthwaite Associates, Pittsgrove, NJ, USA). Wind direction was measured at $z$=40 cm with a propeller-vane wind monitor (model 05103, R.M. Young Inc., Traverse City, MI, USA). These instruments and the HWs were monitored with a programmable data logger (model CR7, Campbell Scientific Inc., Logan, UT, USA).

2.3. High-frequency wind component fluctuations

Longitudinal, lateral, and vertical, $w$, wind components were measured using a tri-axial fibre-film probe (model 55R91, Dantec Measurement Technology, Skovlunde, Denmark) connected to a constant temperature anemometer system (Dantec model 56C01), designated hereafter as TFHW. The tri-axial probe consists of three cylindrical quartz fibres, each plated with nickel and then coated with a thin layer of quartz for protection, which have a frequency response up to 17 kHz. The total diameter of each wire is 75 $\mu$m and the active sensing length is 1.25 mm. The active portions of all three wires are contained within a sphere 3 mm in diameter. The wires are mounted orthogonally to each other and symmetrically about the probe axis so that only incoming wind vectors within a cone of about $\pm 35^\circ$ from this axis are measured unambiguously (without rectification). The probe was calibrated for $0.7 \text{ m s}^{-1} < u < 16 \text{ m s}^{-1}$ in the wind tunnel and for $0.02 \text{ m s}^{-1} < u < 5 \text{ m s}^{-1}$ on the turntable as for the HWs. The more precise turntable calibration at low values of $u$ showed that the calibration from the wind tunnel underestimated $u$ for $u < 2 \text{ m s}^{-1}$. The underestimate varied from about 0.85 at $u=1 \text{ m s}^{-1}$ to about 0.2 at $u=0.05 \text{ m s}^{-1}$. Free convection introduces am-
biguity in the measurements for \( u<0.05 \text{ m s}^{-1} \). The \( u \), \( v \), and \( w \) components were calculated by converting each HW voltage to an effective cooling velocity with King’s law, then transforming these cooling velocities to wind speed along each wire with Jørgensen’s equation, and finally transforming the wire wind speeds to the proper spatial coordinates using an orthogonal coordinate transformation (Bruun, 1995). Each wind vector component was then multiplied by a correction factor for \( u < 2 \text{ m s}^{-1} \) developed from the turntable calibration.

The TFHW measurements were made at \( z=1.0, 3.0, 5.0, 7.6, \text{ and } 9.6 \text{ cm} \) within and above the mulch during the afternoon of 25 August 1994, with the probe facing W–NW. It was mounted on a vertical rod, 1.3 cm in diameter, located about 30 cm downwind of the probe. At least three 10 min periods were recorded at each \( z \). During these measurements, the mean cup wind speed at \( z=57 \text{ cm} \), \( \bar{u}_{57} \), varied in the range 1.3–2.0 m s\(^{-1} \) and the mean above-canopy sensible heat flux density, \( H \), varied in the range 100–220 W m\(^{-2} \) (measured as described in Novak et al. (2000a)). Air temperature, \( T_a \), within 5 mm of the probe was simultaneously measured using a 13 \( \mu \text{m} \) constantan/chromel thermocouple to determine one of the parameters in King’s law which we found depended on temperature. The \( u \), \( v \), \( w \), and \( T_a \) data were monitored simultaneously at 21 Hz using a programmable data logger (model CR10, Campbell Scientific Inc., Logan, UT, USA).

Wind direction above the canopy was also measured at 21 Hz with this logger when the TFHW was in operation (although we recognise that the response of the wind vane was too slow to keep up with this rate). Data from all time intervals within each measurement period for which the wind direction was outside a 30° acceptance sector on either side of the longitudinal axis of the probe were excluded. For measurements within the mulch, the probe was lowered into it through a small hole with a diameter of about 3 cm. After insertion the top of the hole was filled in with pieces of mulch. Since actual distances between mulch elements are smaller than 3 cm (ranging from a few mm to 1–2 cm), measurements made in the hole could differ from those made in the undisturbed mulch (but mainly at the highest frequencies and beyond which were not of prime importance in this study). In addition, wind directions in the mulch are not necessarily the same as those above the canopy. However, Aylor et al. (1993) found by releasing smoke that flow reversals within a few cm of the ground in a grass canopy were rare, except in light winds.

2.4. Determination of turbulence statistics

Friction velocity above the mulch, \( u_* \), was determined from the usual diabatic wind profile (Stathers et al., 1988), as follows:

\[
\frac{k\bar{u}_r}{\ln(z_r - d)/z_0 - \Psi_m},
\]

where \( k=0.4 \) is von Karman’s constant, \( \bar{u}_r \) is the mean horizontal cup wind speed at a reference height, \( z_r=9.6 \text{ cm} \), \( d \) and \( z_0 \) are the displacement height and roughness length, respectively, and \( \Psi_m \) is the diabatic correction for momentum given by

\[
\Psi_m = \begin{cases} \frac{2\ln\left[\frac{(1+x)^2}{2}\right]}{x} + \ln\left[\frac{(1+x^2)^2}{2}\right] \times 2\arctan(x) & \text{for unstable conditions,} \\ \frac{\pi}{2} & \text{for stable conditions,} \\ -4.7\zeta \end{cases}
\]

where \( x=(1-16\zeta)^{1/4} \), \( \zeta=(z_r-d)L_{MO} = -k(z_r-d)gH/(\rho cpT_k u_0^3) \), \( L_{MO} \) is the Monin–Obukhov length, \( g=9.81 \text{ m s}^{-2} \) is the gravitational acceleration, \( \rho=1.2 \text{ kg m}^{-3} \) and \( cp=1020 \text{ J kg}^{-1} \text{ K}^{-1} \) are the density and specific heat at constant pressure of air, respectively, and \( T_k \) is the mean absolute air temperature between \( d+z_0 \) and \( z_r \). Eq. (1) strictly applies only to profiles of \( \bar{u} \), but differences between \( \bar{u} \) and \( \bar{v} \) were small enough (<4% based on the TFHW measurements) that we neglected them. The \( z_r=9.6 \text{ cm} \) differs from the \( z_r=57 \text{ cm} \) reported in Chen et al. (1997b). The latter was in error but calculations show that using \( z_r=57 \text{ cm} \), which is well above the boundary layer in equilibrium with the mulch, would have made little difference. This is because the \( z_0 \) of the upwind bare soil is the same as that of the mulch (Chen et al., 1997b). The values of \( d \) and \( z_0 \) were determined from the HW measurements for near-neutral conditions, when \( \Psi_m \approx 0 \) (described later). Because \( L_{MO} \) is a function of \( u_* \), the calculation of \( u_* \) using Eqs. (1) and (2) was done iteratively.

An independent measurement of \( u_* \) was determined from the TFHW measurements above the mulch as...
\[ u_* = \left(-\frac{\sigma_u}{w_*^2}\right)^{1/2} \], where \( u' \) and \( w' \) refer to the fluctuations of these components about their means and \( w_*^2 \) is the kinematic shear stress. The TFHW also yielded other turbulence statistics, i.e., standard deviations of \( u \) and \( w \) (\( \sigma_u = \left(\frac{\sigma_u^2}{u^2}\right)^{1/2} \) and \( \sigma_w = \left(\frac{\sigma_w^2}{w^2}\right)^{1/2} \), respectively), turbulence intensity for \( u \) and \( w \) (\( i_u = \sigma_u/u \) and \( i_w = \sigma_w/w \), respectively, where \( \sigma_u = \left(\frac{s^2}{u^2}\right)^{1/2} \) with \( s' \) the fluctuation of \( s \) about \( \bar{s} \), skewness of \( s \) (\( Sk_s = \frac{s^3}{\sigma_s^3} \)), and kurtosis of \( s \) (\( Kr_s = \frac{s^4}{\sigma_s^4} \)). Turbulence statistics for \( u \) and \( w \) were similar (generally within 10\% of each other, especially as \( z \) decreased) and the reason we present one or the other is to facilitate comparison with the results of Aylor et al. (1993) whose grass canopy was the most similar in scale to the mulch of all the studies that we found in the literature. It was also possible to calculate the skewness and kurtosis for \( w \) and single-point Eulerian integral time and length scales with the TFHW (all of which are strongly diagnostic of large-scale turbulent structures) but we felt that the values were unreliable within the mulch. This was because the \( w' \)’s were often below the 0.05 m s\(^{-1}\) ambiguity threshold, the 21 Hz sampling frequency (limited by logistical problems in the field) was more than 20 times lower than our normal operating frequency in the wind tunnel (Liu et al., 1996), and the time series was not continuous because the wind direction varied in and out of the acceptance sector of the probe.

Gusts are intermittent events during which large-scale turbulent structures penetrate the canopy from above (Finnigan, 1979). Most of the vertical turbulent transfer into or out of the canopy has been found to occur during the gusts. To examine the intermittency of air flow within the mulch with a view towards identifying gust structures, the mean time between gusts, \( \tau \), and the mean duration of each gust, \( \tau_g \), were calculated from the TFHW measurements. Note that gust duration is generally much shorter than the time between gusts, which are separated by so-called quiescent periods (Chen et al., 1997a). A gust was assumed to begin when the value of \( s \) rose above a preset threshold \( (s = \bar{s} + n\sigma_s) \), with \( n \) an integer in the range of \( 0 \leq n \leq 6 \) and end when the signal dropped below this threshold. Each time a gust occurred an event was counted, with \( \tau \) calculated as the mean time between consecutive event initiations and \( \tau_g \) calculated as the mean time that \( s \) remained above the threshold for each event. The time fraction that \( s \) exceeds the preset threshold is \( f(s) = \tau_g/\tau \). Measured \( f(s) \) was compared to that from the Gumbel extreme distribution (Aylor et al., 1993; note that an error is present in their Eq. (1a)) given by

\[ f(s) = 1 - \exp\left(-\exp\left[-g(s)\right]\right), \]  

where

\[ g(s) = \frac{1.283}{\sigma_s}(s - \bar{s}) + 0.577. \] 

3. Results and discussion

3.1. Cup wind speed above and within the mulch

Fig. 1 shows \( \bar{s} \) plotted versus time, \( t \), within and above the 10 t ha\(^{-1}\) straw mulch during 23–25 August 1994 (note different vertical scales). At all \( z, \bar{s} \) is usually greater during daytime and less at night. Some exceptions occur, e.g., the night of 25 August is quite windy. Cup anemometers often stall at low wind speed, as seen for \( z=24 \) cm at night. Although the magnitude of \( \bar{s} \) decreases as \( z \) decreases, the most striking feature of these time series is their similarity in shape.

![Fig. 1](https://example.com/figure1.png)

Fig. 1. Time series of 10 min average cup wind speed measured using cup anemometers at the 24 and 57 cm heights and the HWs at the 1.1, 3.3, 6.6, and 9.6 cm heights for the 10 t ha\(^{-1}\) mulch during 23–25 August 1994. The top of the mulch is at \( z=6.6 \) cm.
Changes in wind speed initiated (presumably) above the mulch penetrate to all depths in the mulch with little delay, at least on the scale of 10 min. Air flow within the canopy is considerable, the maximum $s$ at the lowest measurement height ($z=1.1$ cm) is 0.18 m s$^{-1}$, which corresponds to 3.7 m s$^{-1}$ at $z=57$ cm.

Values of $\bar{s}$ within and above the mulch are well correlated, as indicated by the large correlation coefficients, $r^2 \geq 0.83$, between wind speed at $z=57$ cm and at lower positions either within or just above the mulch (Fig. 2). The correlation between $\bar{s}$ at $z=57$ and 24 cm was even higher, with $r^2=0.97$ (not shown). This disagrees with Aylor et al. (1993) who found poor correlation ($r^2=0.35$) between $\bar{s}$ at $z=1$ cm and 2 m. Their grass was about four times less dense than our mulch but at least four times taller than the mulch. However, the mulch results are similar to measurements made in a standing wheat residue with a canopy height of 25 cm and an above-ground biomass of 5.8 t ha$^{-1}$ (Heilman et al., 1992). They found that wind speed within and above the residue were closely related, and measured a 15 min mean wind speed of 0.25 m s$^{-1}$ at $z=1$ cm in the residue, which corresponded to 6 m s$^{-1}$ at $z=1$ m above the ground. Our barley-straw mulch was about five times more dense than their stubble.

The ratios $\bar{s}_{1.1}/\bar{s}_{9.6}$ and $\bar{s}_{3.3}/\bar{s}_{9.6}$, where $\bar{s}_{1.1}$, $\bar{s}_{3.3}$, and $\bar{s}_{9.6}$ are $\bar{s}$ at $z=1.1$, 3.3, and 9.6 cm, respectively, are plotted versus $\bar{s}_{57}$ in Fig. 3. At high wind speed ($\bar{s}_{57} > 1.1$ m s$^{-1}$), which usually occurred during daytime, the ratios are nearly constant. However, they increase sharply for lower wind speed conditions, which occurred most often at night. Because wind regimes within and above the mulch in daytime high-wind and nighttime low-wind conditions are apparently different, they will be reported separately.

### 3.1.1. Daytime high-wind conditions

During daytime, a strong inversion of $T_a$ usually existed within the mulch (Novak et al., 2000a). The extent to which this affects $\bar{s}$ within the mulch is shown in Fig. 4, in which $\bar{s}_{1.1}/\bar{s}_{9.6}$ and $\bar{s}_{3.3}/\bar{s}_{9.6}$ are plotted versus the average gradient of $T_a$ between $z=1.1$ and 4.4 cm. $\Delta T_a/\Delta z|_{1.1-4.4}$. The profile of $\bar{T}_a$ was measured with 76 $\mu$m fine-wire constantan/chromel thermocouples at various $z$ within and above the mulch. Only data with $\Delta T_a/\Delta z|_{1.1-4.4} > 0$ (daytime) are shown. The inversion was generally confined to the $z=0-4.4$ cm layer within the mulch and the gradient, which was as high as $3^\circ C$ cm$^{-1}$, is much larger than those in plant canopies, such as the corn canopy of...
Jacobs et al. (1992). Despite the strong temperature inversion in the bottom two-third of the canopy (for which the bulk Richardson number often exceeds the standard criterion of 0.2 for the suppression of turbulence, as seen later), there is no dependence of the ratios on $\frac{T_a}{T_a(z_1)-T_a(z_2)}$, indicating that the inversion has a negligible effect on within-mulch $s$.

This result is attributed to the mulch being too short for significant suppression of turbulence by the stable air layer within it. To see this we calculated a penetration depth, $l_p$, following Jacobs et al. (1992) as

$$l_p = \sigma_w / N,$$

where $\sigma_w$ is evaluated at the mulch top as $1.25u_a$, with $u_a$ determined as described previously, and $N$ is the Brunt–Väisälä frequency given by Plate (1971) as

$$N = \sqrt{\frac{g [T_a(z_2) - T_a(z_1)]}{T_{Ka}(z_2) - T_{Ka}(z_1)}},$$

where $z_1=1.1$ cm, $z_2=4.4$ cm, and $T_{Ka}$ is the mean absolute temperature between $z_1$ and $z_2$. This $l_p$ yields a rough estimate of the height required to convert vertical turbulent kinetic energy to potential energy, neglecting mixing and dissipation (i.e., $l_p$ is an overestimate). Fig. 5 shows that during daytime $l_p>4.4$ cm, the usual depth of the inversion layer, which is at least consistent with little suppression of turbulence by the stable layer. It will be seen later that turbulence within the mulch is of high intensity and highly intermittent, with $\bar{s}$ then strongly determined by turbulent fluctuations, so that suppression of turbulence would affect $\bar{s}$. Calculating $l_p$ for the data of Aylor et al. (1993) ($\sigma_w \approx 0.3 \text{ m s}^{-1}$, $T_a(z_2)-T_a(z_1)\approx 4^\circ\text{C}$, and $z_2-z_1\approx 0.2$ m) with Eqs. (5) and (6) yields 37 cm, which exceeds the typical depth of inversion (10–30 cm) in their study, so that suppression by the inversion apparently does not explain the poor correlation they found between $s$ at $z=1$ cm and that at $z=2$ m.

3.1.2. Nighttime low-wind conditions

Fig. 6 shows that for nighttime ($t=19:00$–$7:00 \text{ hours PST}$) low-wind ($\bar{s}<0.6 \text{ m s}^{-1}$; see Fig. 3) conditions, $\bar{s}_{1.1}$ and $\bar{s}_{3.3}$ are not well correlated with $\bar{s}_{57}(r^2<0.36)$ while they are relatively well correlated with $\bar{s}_{6.6}(r^2>0.70)$. In other words, air flow above the mulch is decoupled from that within, which is similar to observations made in the corn canopy of Jacobs et al. (1992). They found that $\sigma_w$ within the canopy ($z/h=0.41$) at night was nearly constant for a large range of $\sigma_w$ above the canopy ($z/h=2.65$), with $\sigma_w$
within the canopy often exceeding that above it. They attributed this result to within-canopy free-air convection induced by radiation cooling at the canopy top and the relatively warm soil surface, a situation which compares to the convective atmospheric boundary layer.

To find out whether such convection also occurred within the mulch under nighttime low-wind conditions, we calculated the Rayleigh number within the mulch, \( Ra \), under these conditions as follows:

\[
Ra = \frac{\frac{g}{\nu} \left[ T_a(z_2) - T_a(z_1) \right] (z_2 - z_1)^3}{\nu T_{Ka} D_{hm}}
\]

where \( \nu = 1.5 \times 10^{-5} \text{ m}^2 \text{s}^{-1} \) is the kinematic viscosity, \( D_{hm} = 2.2 \times 10^{-5} \text{ m}^2 \text{s}^{-1} \) is the molecular diffusivity for sensible heat, \( z_2 = 6.6 \text{ cm} \) (chosen because at night the minimum \( T_a \) normally occurred at the mulch top), \( z_1 = 1.1 \text{ cm} \) (the lowest measurement height), and \( T_{Ka} \) is the mean absolute temperature between \( z_1 \) and \( z_2 \). When \( Ra > Ra_c = 1706 \) (the critical Rayleigh number), buoyancy work exceeds viscous dissipation, and as a result, the air becomes unstable and motion takes place (Plate, 1971). For the mulch, \( Ra \) is \( 1-2 \) orders of magnitude larger than \( Ra_c \) (Fig. 7). Therefore, free-air convection is expected within the mulch under nighttime low-wind conditions.

According to Plate (1971), the Nusselt number, which is the ratio of actual sensible heat flux density to that which would be transferred only by molecular diffusion, corresponding to \( Ra \approx 10^5 \) should be in the range of \( 2.5-4 \). This is based on both theory and laboratory experiments of free convection in a thin air layer of infinite extent. This enhanced turbulent transfer can explain the high evaporation rates we measured with our modified tension-plate apparatus under the mulch at night (Chen and Novak, 1997). Combining these measured evaporation rates with corresponding differences in water-vapour pressure between \( z = 1.1 \text{ and } 6.6 \text{ cm} \) measured with Vaisalla HMM-20D sensors (Novak et al., 2000a) for the nights during 23–25 August 1994, we calculated the ratio of evaporation rate to that expected by molecular diffusion and found it to be in the range 2.6–4.4, consistent with the above Nusselt numbers. This suggests that the presence of the mulch elements has a small effect on the convection that occurs within the mulch, perhaps not surprising given that the effective mulch porosity (between elements) is about 0.95 (Novak et al., 2000a).

The free-air convection at night explains the good correlations between values of \( \overline{s} \) at different \( z \) within
the mulch and the sharp increase of ratios of $\bar{s}$ within the mulch to that above the mulch (Fig. 3). Jacobs et al. (1992) found a strong relationship between the ratio of $\sigma_w$ in the corn canopy to that above the canopy and the within-canopy bulk Richardson number, $R_i$. Following their approach, we calculated $R_i$ as follows:

$$R_i = \frac{g \left[ T_a(z_2) - T_a(z_1) \right] (z_2 - z_1)}{T_K a \left[ \bar{s}(z_2) - \bar{s}(z_1) \right]^2},$$

with all parameters as in Eq. (7). In Fig. 8, $\bar{s}_{1.1}/\bar{s}_{9.6}$ and $\bar{s}_{3.3}/\bar{s}_{9.6}$ are plotted versus $R_i$ for all data from 23–25 August 1994. Most data points (including all daytime observations) cluster around the near-neutral state ($R_i=0$) with some values extending up to 4 (highly stable), for all of which the ratios remain nearly constant. But during (nighttime) low-wind conditions, when $R_i$ becomes strongly negative (locally unstable), the ratio increases almost linearly as $R_i$ decreases. The fitted linear regressions are given by

$$\bar{s}_{1.1}/\bar{s}_{9.6} = 0.17 - 0.011 \, R_i, \quad r^2 = 0.78, \quad n = 430,$$

(9)

$$\bar{s}_{3.3}/\bar{s}_{9.6} = 0.19 - 0.0096 \, R_i, \quad r^2 = 0.73, \quad n = 430.$$

(10)

This indicates that these ratios are determined mainly by wind and thermal regimes within the mulch (via the bulk $R_i$).

### 3.2. Vertical profile of mean cup wind speed

The vertical profile of $\bar{s}$ varies logarithmically (as expected) with $z$ above the canopy for near-neutral conditions ($t$ in the ranges 7:00–8:00 and 17:00–18:00 hours PST) and exponentially with $z$ within the canopy (Fig. 9). Because all the above-mulch $\bar{s}$ data from the HWs was not collected simultaneously, the fitting of the profile was done by first normalizing each (30 min average) $\bar{s}$ by the corresponding value of $\bar{s}_{57}$ for the above ranges of $t$ on 21 days in 1993 and 1994. All such ratios at each of $z=7.6, 8.6, 9.6, 10.6, 11.1, 11.6, 12.6,$ and $13.6$ cm were then averaged and $d$ and $z_0$ were determined by fitting $\ln[(z-d)/z_0] \ln[(57-d)/z_0]$ (all lengths in cm) to the resulting profile of measured $\bar{s}/\bar{s}_{57}$. This yields $d=0.87h$ (5.7 cm) and $z_0=0.079h$ (0.52 cm). If we...
assume the roughness sublayer is between \( z = h \) and \( z = h + 2(h - d) = 8.3 \text{ cm} \), as in Chen et al. (1997b), then \( z = 7.6 \text{ cm} \) is within this sublayer. The exclusion of this point, however, does not change the logarithmic fitting significantly. The measured data shown in Fig. 9 (both HW, which is the near-neutral data as defined above, and TFHW, which is midday data) are normalized by dividing by the corresponding \( u_* \) determined using Eqs. (1) and (2) as described previously.

Departures from the logarithmic profile due to diabatic influences are expected in principle for most of the day, as indicated by Eqs. (1) and (2). However profiles calculated using these equations show that such departures are generally small just above the mulch, especially for high-wind conditions during daytime (Fig. 9). The curve shown for unstable conditions is calculated with \( H = 300 \text{ W m}^{-2} \) and \( u_* = 0.15 \text{ m s}^{-1} \), appropriate to the most unstable daytime conditions. The stable curve is typical of nighttime low-wind conditions, for which \( H = -20 \text{ W m}^{-2} \) and \( u_* = 0.03 \text{ m s}^{-1} \) were assumed. Therefore, the profile of \( \tau \) above the mulch is nearly logarithmic throughout the day. To within experimental error, TFHW values above the mulch fall on the logarithmic profile measured by the HWs. Measurement errors for both instruments are much larger than the calculated diabatic effects.

The \( d = 0.87h \) agrees well with the models of Raupach (1992) (\( \approx 0.9h \)) and Raupach (1994) (\( \approx 0.85h \)). To apply the former, it was assumed that the fractional area index was equal to one half the (total projected) mulch area index (5.6), as suggested by Raupach (1994). The fitted \( d \) is much higher than the rule-of-thumb estimate of \( 2/3h \) typically applied to vegetative canopies, which is attributed to the high residue-area density of the mulch. The \( z_0 = 0.079h \) is in the range of \( z_0 = 0.066h - 0.1h \) predicted by Raupach (1992, 1994), where the range of values is due to uncertainty in the height of the roughness sublayer. The \( z_0 = 0.1h \) applies if the height of the roughness sublayer is \( h + 2(h - d) \), as assumed by Chen et al. (1997b) for the mulch, and the \( z_0 = 0.066h \) applies if the sublayer is infinitesimally thin. The exact height of the roughness sublayer is unknown but the good fit of the profile below \( z = 7.6 \text{ cm} \) suggests that it should be lower than the \( z = 8.3 \text{ cm} \) assumed previously. The rule-of-thumb estimate for canopies is \( z_0 = 0.1h \), which is about 25% greater than the fitted value. According to the Raupach models, the mulch density exceeds the threshold at which the elements are ‘over-sheltered’, and so the mulch behaves much like the relatively smooth bare soil surrounding it (both have the same \( z_0 \), as discussed in Chen et al., 1997b). The surface drag coefficient, \( C_s = (u_*/\tau)z^2 \approx 0.35 \), where \( \tau \) at \( z = h \), is 2–3 times larger than values typically found for canopies (Raupach, 1992; Massman, 1997). This may be related to the high value of \( d \), which implies that much of the drag is concentrated near the top of the canopy (Thom, 1971) so that \( \tau \) at \( z = h \) is reduced more than in a more open canopy. An unusual feature of the mulch canopy is that the dominant orientation of the roughness elements is horizontal whereas for most canopies it is vertical. This probably plays an important role in explaining why it behaves like a smooth surface with a higher than expected surface drag coefficient.

Since the effects of thermal stratification on within-mulch \( \tau \) are negligible for (generally daytime) high-wind conditions as discussed previously, we use all HW data with \( \tau_{1,1} > 0.08 \text{ m s}^{-1} \) (which corresponds to \( \tau_{37} > 1.1 \text{ m s}^{-1} \)) to calculate the vertical profile within the mulch, with the best-fit exponential function shown in Fig. 9 given by

\[
\tau / u_* = 0.21 \exp \left( \frac{2.2z}{h} \right) 
\]  

(11)

The value of the attenuation factor, 2.2, is somewhat below the range 2.6–4 found in plant canopies (Denmead, 1976; Wilson et al., 1982; Aylor et al., 1993). Denmead (1976) indicates that the attenuation factor decreases as wind speed at the canopy top decreases. As we have seen, \( \tau \) at the top of the mulch is low and therefore the attenuation factor of the mulch is expected to be smaller than that of a plant canopy. Under nighttime low-wind conditions, the attenuation factor is reduced to about 0.5 when within-mulch free convection occurs (not shown). Agreement between the TFHW and HWs within the mulch is reasonably good considering that the wind direction was within the acceptance sector of the TFHW probe for only about 30% of the time.

### 3.3. Turbulence statistics

#### 3.3.1. Friction velocity and higher-order moments

Table 1 shows that agreement is reasonably good between \( u_* \) measured with the TFHW at \( z = 9.6 \text{ cm} \) and...
Table 1
Friction velocity, \(u_\ast\), measured during three 10 min runs with the TFHW at the 7.6 and 9.6 cm heights above the 10 t ha\(^{-1}\) straw mulch vs that from the HW profile method using Eqs. (1) and (2) between 12:20–12:50 hours PST (TFHW at \(z=9.6\) cm) and 13:00–13:30 hours PST (TFHW at \(z=7.6\) cm) on 25 August 1994

<table>
<thead>
<tr>
<th>Run</th>
<th>(u_\ast) (m s(^{-1}))</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFHW, (z=7.6) cm</td>
<td>0.12</td>
<td>0.15</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>HW profile</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>TFHW, (z=9.6) cm</td>
<td>0.15</td>
<td>0.18</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>HW profile</td>
<td>0.17</td>
<td>0.15</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>

that determined using Eqs. (1) and (2) as described previously. At \(z=7.6\) cm, however, the TFHW values are about 25% less than the profile values, which is difficult to explain unless pieces of straw sticking up above \(z=7.6\) cm absorb a significant amount of the drag (we did not measure the variation of straw height about the mean \(h\) adequately to assess this). These results show that despite the low sampling rate and the variation of the wind in and out of the acceptance sector of the probe, the TFHW measurements are meaningful, at least up to second moments above the mulch. According to Brunet et al. (1994), the peak frequency of the \(u'w'\) co-spectrum above a canopy is given by about 0.15\(\overline{u_\ast}/h\), where \(\overline{u_\ast}\) is \(\overline{u}\) at \(z=h\). Using the values in Fig. 9 and Table 1 for midday on 25 August, this expression yields an expected frequency of about 0.7 Hz, which confirms that 21 Hz is adequate for measuring \(u_\ast\). The results also show that the profile method used to determine \(u_\ast\) for all \(t\) is reasonably accurate.

Normalized standard deviations, \(\sigma_u/\overline{u_\ast}\) and \(\sigma_w/\overline{u_\ast}\), vary similarly with \(z\) within and above the mulch (Fig. 10). Although there is scatter in the data, the average values of \(\sigma_u/\overline{u_\ast}\) and \(\sigma_w/\overline{u_\ast}\) at \(z=9.6\) cm (3 and 1.3, respectively) agree reasonably well with typical surface-layer values (2.5 and 1.25, respectively) reported by Raupach et al. (1996). Within the mulch, both \(\sigma_u/\overline{u_\ast}\) and \(\sigma_w/\overline{u_\ast}\) decrease roughly exponentially, as follows:

\[
\sigma_u/\overline{u_\ast} = 0.15 \exp(2.1z/h), \quad r^2 = 0.71, \quad n = 13, \quad (12)
\]

\[
\sigma_w/\overline{u_\ast} = 0.026 \exp(2.9z/h), \quad r^2 = 0.81, \quad n=13. \quad (13)
\]

Data at \(z=7.6\) cm were included in determining these functions because no measurements were taken at \(z=h=6.6\) cm. The rapid decrease of \(\sigma_w/\overline{u_\ast}\) and \(\sigma_u/\overline{u_\ast}\) with decreasing \(z\) near the top of the mulch is in general agreement with the findings of others in grass (Aylor et al., 1993), corn (Wilson et al., 1982), and Douglas-fir canopies (Lee and Black, 1993), although in the latter \(\sigma_u\) increased in the open trunk space below \(z/h=0.5\) (the leaf area density in the forest peaked strongly around \(z/h=0.5\)). Aylor et al. (1993) also fitted exponential profiles to measured \(\sigma_u/\overline{u_\ast}\) and \(\sigma_w/\overline{u_\ast}\) values and found attenuation factors near 2.5 within their grass canopy (their \(r^2\) coefficients, 0.92 and 0.95, respectively, were higher than ours though).

The exponential fit to the profiles in Fig. 10 is poorest near the top of the mulch, where the decrease of \(\sigma_u\) and \(\sigma_w\) is most rapid, i.e., the attenuation within the mulch is actually greater than that indicated by the exponential profiles. Although the profiles of \(\sigma_u/\overline{u_\ast}\) and \(\sigma_w/\overline{u_\ast}\) appear reasonable, they should be interpreted with some skepticism. This is because the \(\sigma\)'s are less than the minimum reliably measured wind speed (0.05 m s\(^{-1}\)) for \(z<1.9\) and 5.4 cm for \(u\) and \(w\), respectively.

Fig. 10. Measured (symbols) and fitted (lines) vertical profiles of horizontal (circles) and vertical (triangles) standard deviations of wind speed normalized by the friction velocity for the 10 t ha\(^{-1}\) mulch. The measurements were made with the TFHW at midday on 25 August 1994. The fitted exponential profiles are given by Eqs. (12) and (13).
the drag occurring very near the top of the mulch (above z=5 cm) as suggested by the value of d'. The variation of sign within the mulch suggests that the within-mulch values are unreliable, most probably because of errors in w.

Turbulence intensity is the simplest indicator of its ‘strength’, with $i_u = \sigma_u / \langle u' \rangle > 0.5$ and $i_w > 0.2$ often designated as in the high range (Bruun, 1995). The $i_u$ and $i_w$ above and within the mulch generally exceed these criteria (Table 2), with $i_u$ increasing somewhat as z decreases within the mulch. This profile of $i_u$ is similar in shape and magnitude to that for the grass canopy of Aylor et al. (1993) and that of $i_u$ measured in the Douglas-fir forest of Lee and Black (1993). The profile shape for $i_u$ is also similar to that in the forest but the magnitudes for the mulch are less, i.e., $i_u = 0.34$ above the forest with a maximum within the forest of 0.68 at $z/h = 0.6$ which is larger than $i_w = 0.24$ above the mulch at $z/h = 1.45$ with a maximum within the mulch of 0.23 at $z/h = 0.5$.

Skewness describes the asymmetry of a probability density distribution. The average Sk$_u$ is 2 at $z = 9.6$ cm (Table 2) which exceeds the 1.15 for a Gumbel extreme value distribution. The value expected if u and v are Gaussian (normally true in the inertial layer) is not zero, because s is restricted to positive values, but should be less than 0.6 (Aylor et al., 1993). As z decreases Sk$_u$ increases, which is in agreement with that for the grass canopy of Aylor et al. (1993) but differs from that for Sk$_u = u'^3 / \sigma^3_u$ in the Douglas-fir forest of Lee and Black (1993). For the forest, Sk$_u$ reached a maximum at $z/h = 0.6$, which was near where the leaf area density was maximum. Given the nearly constant leaf area density for the mulch and the decreasing density with increasing z for the grass a similar maximum for Sk$_u$ is not expected in these canopies. The magnitude of Sk$_u$ for the mulch is as much as two times that for the grass which is attributed to the higher density of the mulch.

Kurtosis is a measure of the peakiness (or intermittancy) of a probability density distribution. For a Gumbel extreme value distribution the kurtosis is 5.37 while for a Gaussian distribution the value is 3. Table 2 shows that Kr$_u$ is close to the value for a Gumbel extreme distribution at z=9.6 cm, which was also found near the top of the grass canopy of Aylor et al. (1993). As z decreases Kr$_u$ increases, which agrees with the profile in the grass and differs from Kr$_u = u'^4 / \sigma^4_u$ within the Douglas-fir forest of Lee and Black (1993) as found for skewness. The Kr$_u$ is up to five times that of the grass, which again is attributed to the higher density of the mulch. For the forest Kr$_u$ was as high as 5 at $z/h = 0.6$. The Sk$_u$ and Kr$_u$ within the mulch are consistent with the existence of gusts of fast-moving air from above the mulch penetrating the canopy intermittently (Shaw and Seginer, 1987).

It is instructive to consider why we did not consider single-point Eulerian integral time and length scales measured with the TFHW to be reliable, as these would have yielded direct measurements of the size of the dominant turbulent structures. According to the data in Fig. 9 and Table 1, $\overline{\sigma_u} = 0.3$ m s$^{-1}$, so that if the size of the large-scale active eddies is $\sim h = 6.6$ cm (this is probably an upper limit for the dense mulch), then the time for the eddy to drift pass a measuring position at the top of the mulch is $\sim 0.2$ s. To accurately delineate the eddy would require sampling at least every 0.02 s or 50 Hz, which is more than twice the sampling.

---

Table 2
The vertical profiles of turbulent statistics measured with the TFHW$^a$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$z$ (cm)</th>
<th>$t$ (hours PST)</th>
<th>$\overline{v}$ (m s$^{-1}$)</th>
<th>$\overline{u'w'}$ (m$^2$ s$^{-2}$)</th>
<th>$i_u$</th>
<th>$i_w$</th>
<th>Sk$_u$</th>
<th>Kr$_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
<td>12:20–12:50</td>
<td>0.95</td>
<td>$-2.9 \times 10^{-2}$</td>
<td>0.65</td>
<td>0.25</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>7.6</td>
<td>13:00–13:30</td>
<td>0.55</td>
<td>$-1.8 \times 10^{-2}$</td>
<td>0.7</td>
<td>0.25</td>
<td>2</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>13:30–14:00</td>
<td>0.1</td>
<td>$2.3 \times 10^{-4}$</td>
<td>0.65</td>
<td>0.15</td>
<td>3</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14:10–14:50</td>
<td>0.065</td>
<td>$-9.3 \times 10^{-4}$</td>
<td>0.75</td>
<td>0.25</td>
<td>3</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14:50–15:20</td>
<td>0.04</td>
<td>$2.3 \times 10^{-4}$</td>
<td>0.9</td>
<td>0.15</td>
<td>4</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

$^a$: $\overline{v}$: Mean cup wind speed; $u'w'$: kinematic shear stress; $i_u$: cup turbulence intensity; $i_w$: vertical turbulence intensity; Sk$_u$: cup wind skewness; Kr$_u$: cup wind kurtosis; $z$: heights within and above the 10 t ha$^{-1}$ straw mulch; and $t$: times on 25 August 1994. Values are averages of three or four ($z=3$ cm) 10 min runs with significant figures determined by the variability between runs.
rate used. For smaller structures the sampling would have to be even faster. Aylor et al. (1993) found turbulent length scales \( \sim 1 \text{ cm} \) within the grass canopy. A similar calculation based on their data suggests that these scales are also marginally reliable (they sampled at 20 Hz). In Novak et al. (2000a) we present an estimate for the vertical single-point integral length scale calculated by dividing the measured far-field diffusivity for water vapour by \( \sigma_w \) determined from Eq. (13) and Table 1.

3.3.2. Frequency distribution of extreme wind speed

Fig. 11 shows that \( s \) is indeed highly intermittent near the bottom of the mulch, as is often observed (but less extremely so) in plant canopies (Shaw et al., 1983; Aylor et al., 1993). The mean \( s \) of this 1 min sample is 0.077 m s\(^{-1}\), with a maximum of 0.62 m s\(^{-1}\). As a result, the fraction of time that \( s \) exceeds \( \bar{s} \) by integer multiples of \( \sigma_s \) is small (Fig. 12). For example, \( s \) exceeds \( \bar{s} + \sigma_s \) only 13% of the time, which decreases to 4% for a threshold of \( \bar{s} + 2\sigma_s \). The Gumbel extreme value distribution predicts these measured fractions reasonably well except at larger thresholds, for which the prediction tends to underestimate for \( z < h \). Our findings are in general agreement with those observed in other experimental studies (Baldocchi and Meyers, 1988; Aylor et al., 1993).

If we assume that the frequency of large-scale eddies (or coherent turbulent structures) can be approximated by the frequency of gusts, then it is of great interest to see how the latter varies with threshold speed. Table 3 shows \( \tau \) (the inverse of gust event occurrence frequency based on \( s \approx u, f_u \)) for three threshold values of \( s \). Note that \( \tau \) is approximately constant with \( z \) for each threshold, which is consistent with the horizontal dimension of the coherent structures being \( \sim h \) (Raupach et al., 1996). As the threshold increases \( \tau \) also increases, i.e., fewer events are detected, which shows the arbitrariness of the threshold setting. Average values of \( \tau \) are 0.58, 1.03, and 2.22 s corresponding to thresholds defined by \( (s - \bar{s})/\sigma_s = 0, 1, \) and 2, respectively.

The Mexican Hat wavelet transform can determine \( \tau \) more objectively (Collineau and Brunet, 1993a, b). In a separate study we applied this transform to 80 Hz air temperature time series measured above the mulch at \( z = 9.6 \text{ cm} \) and found \( \tau \approx 1 \text{ s} \) (Chen et al., 1997a). Even with the arbitrariness of the threshold, the two methods agree to within a factor of 2. According to Collineau and Brunet (1993b) and Brunet and Collineau (1994), as reported by Raupach et al. (1996), frequencies based on \( u \) time series are expected to be about 1.8 times lower than those based on \( T_a \) and about three times lower than those based on \( w \). The latter are considered to be the most diag-
Table 3
Mean time between events defined by the cup wind speed exceeding a specified threshold, $\tau$, and mean duration of events, $\tau_g$, for three thresholds, at the indicated heights, $z$, within and above the $10 \text{t ha}^{-1}$ straw mulch and times, $t$, on 25 August, 1994

<table>
<thead>
<tr>
<th>$z$ (cm)</th>
<th>$t$ (hours PST)</th>
<th>$\tau$</th>
<th>$\tau + \sigma_\tau$</th>
<th>$\tau + 2\sigma_\tau$</th>
<th>$\tau_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
<td>12:20–12:50</td>
<td>0.57</td>
<td>0.95</td>
<td>2.3</td>
<td>0.24</td>
</tr>
<tr>
<td>7.6</td>
<td>13:00–13:30</td>
<td>0.42</td>
<td>0.70</td>
<td>1.6</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>13:30–14:00</td>
<td>0.44</td>
<td>0.81</td>
<td>2.0</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>14:10–14:50</td>
<td>0.71</td>
<td>1.1</td>
<td>2.4</td>
<td>0.29</td>
</tr>
<tr>
<td>1</td>
<td>14:50–15:20</td>
<td>0.76</td>
<td>1.6</td>
<td>2.9</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Diagnostic of turbulent structures produced by shear at the canopy top. If this holds for the mulch then the proper threshold is about halfway between $\bar{u} + \sigma_\bar{u}$ and $\bar{u} + 2\sigma_\bar{u}$.

Raupach et al. (1996) showed that for a number of different sized and shaped canopies, both in the field and wind tunnel, $f$ based on $w$, $f_w$, should scale as follows:

$$f_w = \left( \frac{1.8h}{8.1L_s} \right) \left( \frac{\bar{u}_h}{h} \right) = \beta_w \left( \frac{\bar{u}_h}{h} \right). \quad (14)$$

where $L_s = u_h/d\bar{u}/dz|_{z=h}$. Note, that after substitution of the definition of $L_s$ this is equivalent to $f_w = 0.22d\bar{u}/dz|_{z=h}$, i.e., $f_w$ is proportional to the shear at the canopy top. Typically, $L_s \approx 0.92h$ which yields $0.44$ for $\beta_w$ in Eq. (14). The equivalent $\beta$ value for $f_0$ is then $\beta_0 = 0.44/3 = 0.15$. Estimating $L_s$ more accurately from the near-neutral profile of $\bar{u}/u_a$ versus $z/h$ shown in Fig. 9 (ignoring differences between $\bar{u}$ and $\bar{u})$ yields $L_s \approx 0.32h$, and therefore an expected $\beta_0 = 0.23$.

By setting the threshold speed to $\bar{u} + \sigma_\bar{u}$, Aylor et al. (1993) found $\beta_0 = 0.07$ for their grass canopy. For the mulch, substituting measured $\bar{u}_h \approx \bar{u}_h$ and $\tau$ (equal to $1/f_0 = 3f_w$) into Eq. (14) (after dividing both sides by $3$) yields $\beta_u (= \beta_u/3)$ values of $0.35$, $0.19$, and $0.10$ corresponding to threshold speeds, $(s - \bar{u})/\sigma_u = 0$, 1, and 2, respectively. If the proper threshold is between $\bar{u} + \sigma_\bar{u}$ and $\bar{u} + 2\sigma_\bar{u}$, as suggested earlier, then agreement is excellent with the generic value of $L_s$ ($\beta_u = 0.15$) and overestimated by about $60\%$ with $L_s = 0.32h$ calculated for the mulch ($\beta_u = 0.23$). Therefore, the suggestion of Raupach et al. (1996) that wind shear near the top of a canopy offers a reasonable basis for scaling the frequency of gusts is approximately valid even for a short dense mulch.

4. Summary and conclusions

Despite the fact that the barley-straw mulch studied is much shorter and denser than most plant canopies, considerable air flow occurs within it, e.g., we recorded at midday an instantaneous cup wind speed of $0.62 \text{ m s}^{-1}$ at $z = 1 \text{ cm}$ within the $10 \text{t ha}^{-1}$ mulch. Within-mulch mean cup wind speed is generally well correlated with that above during high-wind conditions, which usually occur during daytime. Then the ratio of within-mulch to above-canopy cup wind speed remains nearly constant at each height for a variety of wind speeds at a reference height above the mulch. As a result, the mean wind profile is described by a near-logarithmic profile above the canopy and by an exponential profile within the canopy. The highly stable thermal stratification inside the mulch during daytime has little effect on the ratios of within-mulch to above-canopy mean cup wind speed.

Under nocturnal low-wind conditions ($\bar{u}_z < 0.6 \text{ m s}^{-1}$), radiation cooling at the canopy top and the relatively warm soil surface leads to unstable atmospheric conditions within the mulch while conditions are stable above the mulch. The Rayleigh number within the mulch is then $1-2$ orders of magnitude larger than the critical value required for the onset of convection. As a result, mean cup wind speeds are well correlated with each other within the mulch but not to wind speed above the mulch.
The ratio of within-mulch to above-canopy mean cup wind speed then increases sharply in a manner that is well-described by a linear dependence on bulk Richardson number across the mulch.

During daytime, air flow within and above the mulch is of high turbulence intensity. The mulch is aerodynamically quite smooth with a roughness length similar to the surrounding bare soil. The displacement height and profile of kinematic shear stress indicate that most of the drag occurs very near the top of the mulch which apparently increases the canopy drag coefficient above that found for most plant canopies. The dominantly horizontal orientation of the mulch elements probably plays a role in this behaviour. Mean cup wind speed and standard deviations of horizontal and vertical wind components all increase exponentially with height within the mulch. In the surface layer above the mulch the ratio of the standard deviations of horizontal and vertical wind fluctuations to the friction velocity agree with the values found above plant canopies. Wind speed within and just above the mulch is highly intermittent and dominated by gusts, as indicated by large values of skewness and kurtosis for fluctuations in the magnitude of the cup wind speed. The extremes of these fluctuations are described fairly well by a Gumbel distribution, especially near the top of the mulch. The frequency of these fluctuations is in reasonably good agreement with a relationship suggested by Raupach et al. (1996) based on the supposition that the dominant turbulence in canopies is generated by shear at the canopy top and therefore resembles that in a laboratory mixing layer.

In summary, the wind and turbulence regimes in the straw mulch resemble in many ways those in plant canopies much larger in height and lower in leaf area density. In Novak et al. (2000a) we use the results presented here to interpret and explain the sensible and latent heat fluxes measured within and above the straw mulch.

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