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The budgets of turbulent kinetic energy and Reynolds stress within and above a deciduous forest*

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ABSTRACT

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Mean turbulence statistics obtained within and above a deciduous forest are used to examine the components in the budget equations for turbulent kinetic energy (TKE) and tangential shear stress. Comparisons from the measurements are made with predictions from a higher-order closure model for canopy flow. Wake-generated turbulence was found to exceed shear-produced turbulence in all but the upper level of the canopy. Beneath the tree crowns, turbulent transport was the dominant source of TKE and tangential shear stress. Below ~75% of the canopy height, the magnitude of all the TKE and shear stress budget components is small compared with values above this height, and the vertical gradients of second- and third-order moments are small. The turbulence statistics observed within the deciduous forest are remarkably similar to that observed within a tropical forest, which has a similar distribution of leaf area. When compared with results from experiments conducted in other canopies, the importance of the quantity and vertical distribution of the plant area in determining the turbulence structure is reinforced.

INTRODUCTION

The turbulence structure in a plant canopy environment is affected by dynamic complex plant–atmosphere interactions that occur on both large and small scales. The mean wind speed within a plant canopy depends on how effective a fast-moving turbulent eddy originating from the atmospheric boundary layer can penetrate a canopy layer, as well as the effectiveness with which plant canopy elements can absorb momentum through form and viscous drag. Turbulence intensities inside a canopy depend upon the mechanical and convective processes in the surface and planetary boundary layers,

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the transport of this turbulent energy to the canopy layer and the breakdown of the scales of motion that penetrate the canopy into smaller scales in the wakes of the plant elements. Eulerian models, whose set of equations is closed at the second or third order, have been used to describe the average turbulence structure by attempting to account for the processes mentioned above. In most instances, these models are evaluated for their ability to reproduce mean velocity, temperature and humidity fields, and their corresponding above-canopy fluxes. Efforts to examine other turbulence statistics such as triple velocity products and the terms in the budget equations for the second moments (i.e. tangential shear stress and normal variances) within real plant canopies have been hampered by the enormous experimental requirements necessary to make such an assessment. Measurements from wind tunnel experiments (Raupach et al., 1987; Coppin et al., 1987) have provided some insight into the average turbulence structure and the processes that govern the mean turbulent field. Some of the terms in the second-order equations can be determined directly from measurements while others, such as the pressure gradient interaction terms, cannot yet be measured; the best estimates of the magnitude of these terms are usually obtained by residual analysis. Results of observed turbulent structure for heat, momentum and turbulent kinetic energy (TKE) from wind tunnel studies have been compared to predictions from models (see Meyers and Paw U, 1987).

Within the past few years, several ambitious field campaigns have been conducted to further our understanding of turbulent transport processes within real plant canopies. During the fall of 1986, we collected wind velocity data within and above a fully leafed deciduous forest. In this paper, vertical profiles of relevant first-, second- and third-order statistics are presented, along with estimates of the terms in the second-order shear stress and TKE budget equations. The results determined from the measurements are compared with those derived from a higher-order closure model (Meyers and Paw U, 1986). A conditional sampling and spectral analysis of the data collected from this experiment are discussed elsewhere (Baldocchi and Meyers, 1988a, b).

EXPERIMENTAL PROCEDURES

The experiment was conducted at the National Oceanic and Atmospheric Administration Atmospheric Turbulence and Diffusion Division's research site on the U.S. Department of Energy's Reservation near Oak Ridge, TN. The site is located on a gentle ridge within an undisturbed oak–hickory–loblolly pine forest. The site consists of a 44-m walkup tower with an adjacent 33-m triangular tower for instrumentation. A full description of the plant species and canopy architecture is given by Hutchison et al. (1986). At the time of the experiment, the canopy was fully leafed with a leaf area index (LAI) of ~5 and the mean canopy height (h_c) was estimated to be ~23 m. From

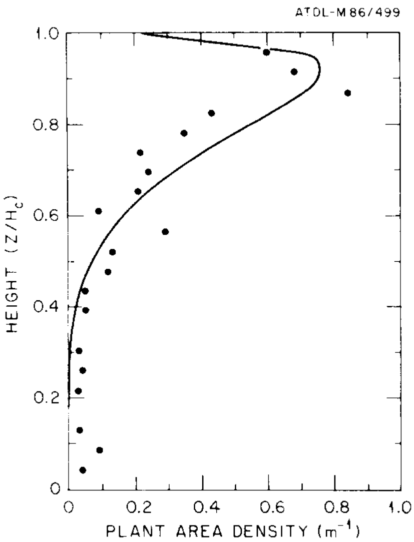

Fig. 1. Vertical distribution of the leaf area for an eastern hardwood oak-hickory forest. A Beta distribution (solid line) was fitted to the data (●) (adapted from Hutchison et al., 1986).

Fig. 1, it can be seen that most of the leaf area is contained in the upper 5 m of the canopy, which is typical of eastern U.S. hardwood forests. It is this particular feature, which will be discussed later, that makes the observed turbulence structure within these forests unique when compared with other forest and crop canopies.

The wind speed in the streamwise, vertical and transverse directions was measured with sonic anemometry both within and above the canopy. Measurements of wind speed were made at 24, 22, 20.7, 18, 10, 6.9 and 2.6 m above the forest floor. A Gill anemometer and a microbead thermistor were mounted at 34 to measure the wind vectors and temperature fluctuations, and consequently the sensible heat flux. Further details of the site and experiment are described by Baldocchi and Meyers (1988a, b).

Generation of vertical profiles of turbulence statistics

In order to evaluate the magnitude of several components in the budget equations for the TKE and tangential stress, vertical profiles are needed for several turbulence statistics. It was not possible to make measurements at all heights simultaneously with only three sonic anemometers. Therefore, vertical profiles of turbulence statistics were obtained by pooling together data from only near-neutral to slightly unstable conditions and normalizing the velocity statistics using the friction velocity, u_*, measured above the canopy. After normalizing the turbulence statistics, means and standard errors were computed at each measurement height by pooling statistics from a number of half-hour runs to obtain a statistically stable value (see Baldocchi and Meyers, 1988a). Using this procedure, the sampling error was found to be < 15% (see Lumley and Panofsky, 1964). The normalized means and standard errors of the turbulence statistics of interest were then plotted as a function of height. The vertical profiles were smoothed and digitized so that vertical gradients could be calculated.

Theoretical framework for analysis

By examining the mean turbulence structure, some insight into the relative importance of some of the turbulence transport processes for a particular canopy type can be gained. One approach is to examine the magnitude of the components in the mean TKE and shear stress budget equations. Assuming that local time rate of change terms are negligible, the volume-averaged budget equations (assuming horizontal homogeneity and neutral stratification) for TKE and tangential stress can be written as

$$\frac{\partial\langle\overline{q^2}/2\rangle}{\partial t}=0=-\langle\overline{u'w'}\rangle\frac{\partial\langle\bar{u}\rangle}{\partial z}-\frac{\partial\langle\overline{w'q^2}/2\rangle}{\partial z}-\frac{\partial\langle\overline{p'w'}\rangle}{\partial z}+\langle\bar{u}\rangle f_{\mathrm{d}}-\langle\epsilon\rangle \qquad (1)$$

$$\qquad\mathrm{Ia}\qquad\qquad\mathrm{IIa}\qquad\qquad\mathrm{IIIa}\qquad\qquad\mathrm{IVu}\qquad\qquad\mathrm{Va}$$

$$\frac{\partial\langle\overline{u'w'}\rangle}{\partial t}=0=-\langle\overline{w'^2}\rangle\frac{\partial\langle\bar{\mathrm{u}}\rangle}{\partial z}-\frac{\partial\langle\overline{\mathrm{w}'^2\mathrm{u}'}\rangle}{\partial z}-\left\langle\overline{\mathrm{u}'\frac{\partial\mathrm{p}'}{\partial z}}+\overline{\mathrm{w}'\frac{\partial\mathrm{p}'}{\partial\mathrm{x}}}\right\rangle \qquad (2)$$

$$\qquad\mathrm{Ib}\qquad\qquad\mathrm{IIb}\qquad\qquad\mathrm{IIIb}$$

where the brackets denote a volume average and the overbars indicate a time average. Here, u is the streamwise (x-direction) component of the wind vector, w is the vertical (z-direction) component, p is the kinematic pressure, ϵ is the viscous dissipation rate of TKE, where TKE$=\overline{q^2}/2$ ($\overline{q^2}=\overline{u'^2}+\overline{v'^2}+\overline{w'^2}$) and f_{d} is the effective aerodynamic drag force imposed on the mean flow by the canopy elements. The primed quantities denote the corresponding deviations from the temporal mean. The first terms (Ia and Ib) are local shear production of turbulence which arise from turbulent interactions with the mean wind profile. The divergence of the triple correlations or turbulent transport terms (IIa and IIb) are the non-local contribution to stress or TKE. The fourth term in eqn. 1 represents the work done by the mean flow against form drag and the subsequent conversion into TKE in the wakes of the canopy elements. The viscous dissipation rate (ϵ) is the ultimate sink of TKE, which destroys turbulent motions at scales small enough to be attacked by viscosity and consequently converted into heat. The pressure gradient interaction terms (IIIb) act to destroy correlations that compose the shear stress. The buoyancy terms in both equations have been neglected in this analysis since the data were analyzed from selected periods when the atmospheric stabilities ranged from near neutral to slightly unstable. This was done since heat flux measurements could not be made simultaneously at all heights. Dispersive terms, which arise from correlations in deviations from spatial averages, were conveniently assumed to be negligible since we could not assess their magnitudes from our data set. Data from wind tunnel studies, however, suggest that dispersive terms are small relative to the other terms in the budget equations (Raupach et al., 1987). In order to make an assessment of the components in the second-order budget equations, it was assumed that the measurements from different heights at a given location were representative of the volume averages, since measurements were available from only one location.

From the digitized profiles, the local shear production (Ia and Ib), turbulent transport (IIa and IIb) and wake production (IVa) terms were evaluated. The fluctuating pressure–velocity interaction term (IIIb) from eqn. 2, along with the sum of the pressure transport (IIIa) and dissipation rate (IVa) from eqn. 1, were determined as residuals. Any uncertainties or errors in the determination of the local production and transport terms are combined in the residual. For the purpose of comparison and model evaluation, equivalent terms were generated from a higher-order closure model for canopy flow described by Meyers and Paw U (1986).

Some slight modifications in the model have been made. Most notably, the methodology for computing the within-canopy length scale was modified. This length scale is used in the calculation of the turbulence time scale and in the parameterization of $\langle \epsilon \rangle$. Recent experimental evidence suggests that vertical integral length scales are relatively constant in the lower canopy (Raupach, 1988). These scales are associated with intermittent turbulent eddies that are energetic and large enough to penetrate the canopy crowns and enter the sub-canopy trunk space. These large, but infrequent events, are responsible for much of the turbulent exchange. Using conditional sampling techniques, Baldocchi and Meyers (1988a) found that within the sub-canopy trunk space of a deciduous forest, $>50\%$ of the momentum flux was generated by events that were 20 times the average flux, but occurred only 10% of the time. In higher-order closure models, a length scale is needed for most of the parameterizations. In the past, the within-canopy length scale was usually determined as a function of the plant area density, drag coefficient and height with the gradient of the length scale not allowed to exceed some predetermined value that is normally on the order of the von Karman constant, k (Seginer et al., 1976; Wilson and Shaw, 1977). This is a valid assumption for airflow in the neutral atmospheric surface layer where a log profile of the mean wind is generally found. Several trial simulations using constant length in the lower canopy produced velocity variances and gradients that matched observations better than using the more 'standard' method. In the model computations that follow, it was assumed that the length scale below the height of the momentum zero plane (d_m) is constant and is proportional to d_m, which was calculated to be ~ 19 m ($d_m/h_c=0.83$) using the center of 'mass' or pressure method (Thom, 1975).

RESULTS AND DISCUSSION

Mean wind profile

Figure 2 shows the mean wind profile, non-dimensionalized using the canopy height (h_c) and the friction velocity (u_*) above the canopy. A zone of strong shear exists in the upper part of the canopy where the foliage is most concentrated, and a significant secondary wind maximum is present in the middle and lower canopy. The measured mean wind profile from this experiment compares more favorably with the data obtained by Pinker and Holland (1987) for a tropical forest in Thailand than with the mean wind profile data presented by Gao et al. (1989) for a deciduous forest in southern On-

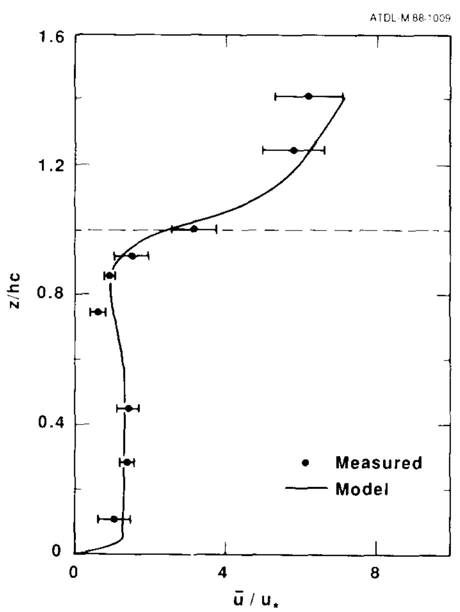

Fig. 2. Vertical profile of mean wind ($\bar{u}$) normalized by the friction velocity (u_*). Also shown are the standard deviations of the measurements at each height (z) which is normalized by the canopy height (h_c).

tario, Canada. The vertical distribution of leaf area for the tropical forest site and the eastern U.S. site presented here are probably very similar, with the tropical forest site having a zero-plane displacement on the order of 30 m (Thompson and Pinker, 1975) which in a non-dimensional form ($z/h_c = 0.85$) is close to that determined for our site. This implies that most of the leaf area is concentrated in the very upper portion of the canopy (Shaw and Pereira, 1980). The peak of the leaf area distribution for the Canadian site is located at $z/h_c = 0.75$ (Neumann et al., 1989), which is lower than the peak ($z/h_c = 0.9$) for the deciduous forest discussed in this paper. Both the deciduous and tropical forest exhibit a wind speed minimum near $z/h_c = 0.75$, while that for the Canadian deciduous forest is located in the vicinity of $z/h_c = 0.5$.

In general, the modeled mean wind profile falls within the standard error of the measured mean wind at the measurement heights. The strengths of the modeled wind speed minimum and the secondary wind maximum in the trunk space are that they are in fairly good agreement with the measurements. For a secondary wind maximum to occur, the turbulent transport term (IIb) has to exceed the pressure term (IIIb) to force a reversal in the mean wind gradient (Shaw, 1977). Intuitively, this can be realized by envisioning an ensemble of large turbulent eddies moving downward through the canopy ($\overline{w'w'u'}$ is positive). At the forest floor, all air motions approach zero velocity ($\overline{w'w'u'} = 0$), thus $\partial\langle\overline{w'w'u'}\rangle/\partial z > 0$. On the average, this downward movement is directed into a horizontal motion in the direction of the mean wind, resulting in a reversal of the mean wind gradient producing a 'jet-like' structure. The 'jets' associated with these infrequent, but energetic turbulent events, when time averaged are realized in the form of a secondary wind maximum structure.

Second moments

The vertical profiles of the second moments (components of TKE and tangential stress) shown in Fig. 3 reveal a unique structure that differs from results obtained for other canopies. All three TKE components ($\overline{u'^2}$, $\overline{v'^2}$ and $\overline{w'^2}$; Figs. 3a, b and c) are reduced to ~10% of their above canopy values at $z/h_c = 0.75$. This is a rather dramatic gradient when compared to the profiles of the TKE components obtained in a corn canopy (Shaw et al., 1974; Wilson et al., 1981), a coniferous forest (Raupach, 1988) and another deciduous forest (Shaw et al., 1988). Below this level in the canopy, the gradients of the TKE components are small. The zero-gradient zone spanning from $z/h_c = 0.8$ to near the bottom of the canopy was not well reproduced by the model, which produced a near constant gradient for all three velocity variances within this zone. The tangential shear stress, $\langle\overline{u'w'}\rangle$, drops off even more rapidly than the TKE components and attains a relatively constant value below $z/h_c = 0.6$.

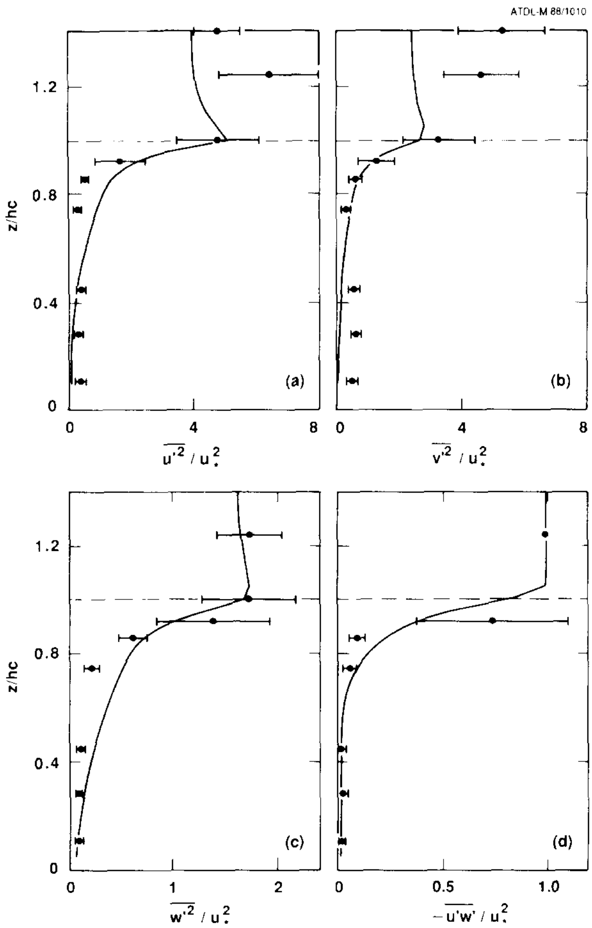

Fig. 3. Vertical profiles of the normalized velocity variances ($\overline{u'^2}/u_*^2$, $\overline{v'^2}/u_*^2$, and $\overline{w'^2}/u_*^2$) and shear stress ($\overline{u'w'}/u_*^2$) within and above the canopy.

About 90% of the total momentum absorption by the canopy is absorbed in the upper 20% of the canopy compared to the Canadian deciduous forest where ~90% of the total momentum absorption occurs in the upper 40% of the canopy (Shaw et al., 1988).

A comparison of our measured turbulence statistics with those from other canopies is shown in Fig. 4. The striking differences are the large gradients in the present measurements for the TKE and shear stress components in the upper canopy. Similar to the mean wind profile are the second moment statistics which resemble those for a tropical forest (Pinker and Holland, 1987). The unique structure observed in both the deciduous forest and in the tropical forest can be attributed to similar vertical distributions of leaf area, where 75% of the leaf area is concentrated in the upper 20% of the canopy (Hutch-

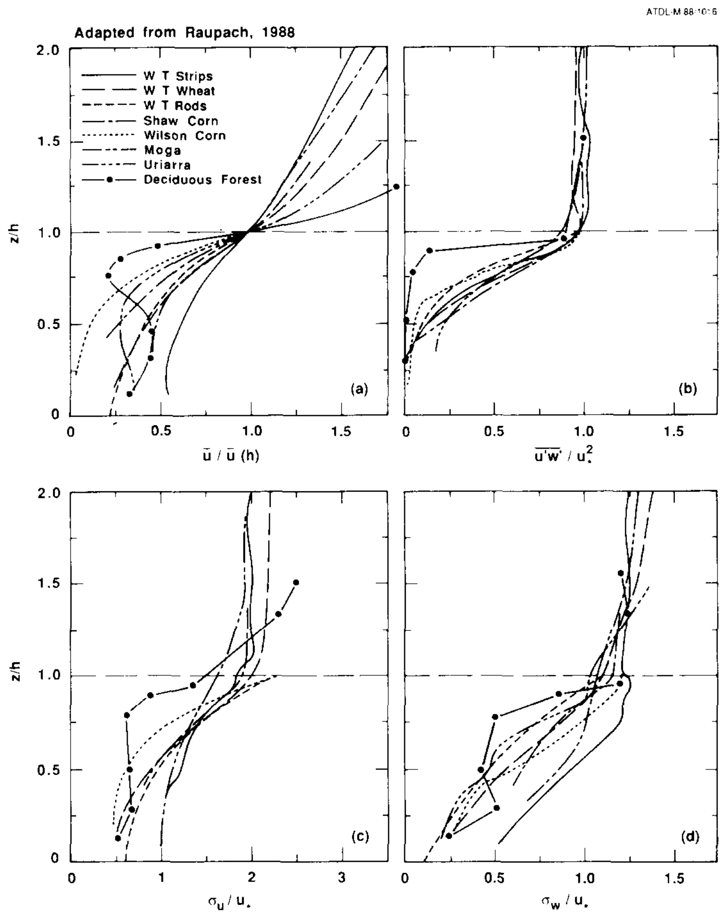

Fig. 4. A comparison of mean wind and turbulence profiles for various canopy structures (adapted from Raupach, 1988).

ison et al., 1986). This accounts for the observations that show that at $z/h_c = 0.9$ nearly 80% of the total momentum is already absorbed.

Third moments

The triple moments of interest are those that appear in the TKE and tangential stress budget equations, namely, $\overline{w'u'^2}$, $\overline{w'v'^2}$, $\overline{w'^3}$ and $\overline{w'^2u'}$. As with the second moments, large vertical gradients are observed for the triple velocity products in the upper canopy (Fig. 5). The third moments $\overline{w'^3}$, $\overline{w'v'^2}$ and $\overline{w'u'^2}$ are negative because the canopy acts as a sink for turbulent motions. As expected, $\overline{w'^2u'}$ is positive since the canopy is a sink for momentum (i.e. $\overline{u'w'} < 0$). The overall profile patterns are similar to what Shaw and Seginer (1987) found for both a maize and an artificial canopy with magnitudes

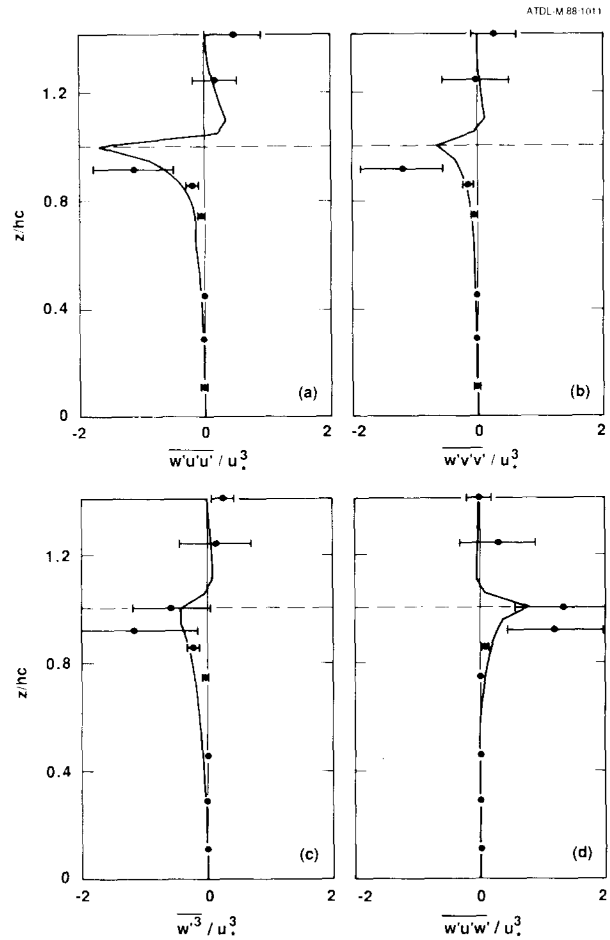

Fig. 5. Vertical profiles of the triple velocity products ($\overline{w'u'^2}$, $\overline{w'v'^2}$, $\overline{w'^3}$ and $\overline{w'^2u'}$) which are normalized by u_*^3.

peaking in the upper canopy and tending towards 0 above and below the peak. However, the gradients observed in this study are much steeper than those presented by Shaw and Seginer (1987) and are due to differences in the vertical distribution of plant area. Below $z/h_c = 0.75$, which is near the base of the tree crowns, the measured third-order terms are not discernable from 0 (Fig. 5). The underestimation of the triple moments by the model is not surprising since the modeled triple velocity products are proportional to the gradients of the second-order quantities (see Meyers and Paw U, 1986), which were generally underestimated by the model. In the model of Meyers and Paw U (1986), the set of equations at the third order is closed by making assumptions about the quadruple velocity products that appear in the rate equations for the third-order moments. Briefly, the quasi-Gaussian approximation for the quadruple moments used in the approximate rate equations for the triple moment assumes that

$$\overline{u_i'u_j'u_k'u_l'} = \overline{u_i'u_j'}\,\overline{u_k'u_l'} + \overline{u_i'u_k'}\,\overline{u_l'u_j'} + \overline{u_i'u_l'}\,\overline{u_j'u_k'} \qquad (3)$$

Shaw and Seginer (1987) found that using measured quadruple velocity products instead of approximating them with eqn. 3 gave only a marginal improvement in the prediction of the third moments. This suggests that the quasi-Gaussian assumption is adequate for canopy flow turbulence models that are closed at the third order. They also found that calculated third moments tended to peak at higher levels than measured moments within both an artificial canopy and a corn canopy. There is evidence of this pattern in our data as well (Fig. 5). Considering the statistical nature of third moments, as well as the uncertainty in the turbulence closure parameterizations, the gross features of the measured vertical profiles of the triple velocity products are reproduced fairly well by the model. In particular, observed peaks in the profiles and magnitudes of the triple moments corresponding to the components in the TKE budget are generally within the uncertainty of the measurements. Likewise, both measured and modeled values of $\overline{w'^2u'}$ are positive, and peak values are seen near the top of the canopy.

Turbulent kinetic energy budget

The measured and modeled components of the TKE budget, shown in Fig. 6, reveal that below $z/h_c=0.75$, the magnitudes of the various components are small compared to their values near the top of the canopy. Wake production of TKE (P_w) slightly exceeds shear production (P_s) at all levels, except near the top of the canopy, where both $\overline{u'w'}$ and the mean wind shear are near peak levels. At $z/h_c=0.9$, wake production of TKE is still of considerable magnitude; however, the velocity variances are diminished to <25% of their above-canopy magnitudes (see Fig. 3). Although the wake production rate of TKE is relatively large in magnitude, the scales of motion generated in the wakes of the plant canopy elements do not contribute greatly to the velocity variances (Raupach and Shaw, 1982) as these motions are quickly dissipated into heat by viscosity. Eulerian-based closure models tend to overestimate the within-canopy velocity variances (as shown in Fig. 3), especially at heights where wake production of TKE is large. This occurs because the dissipation rate of TKE (ϵ) is usually parameterized as a function of q^3/λ where λ is a length scale. The plant canopy elements convert mean kinetic energy (MKE) and low-frequency (i.e. large eddies) shear produced and imported TKE into high-frequency motions (small eddies) that can be quickly dissipated. This may explain why the observed power spectra (see Amiro and Davis, 1988; Baldocchi and Meyers, 1988b) for all three velocity components within the plant canopy roll off faster than what is observed above plant canopy and in

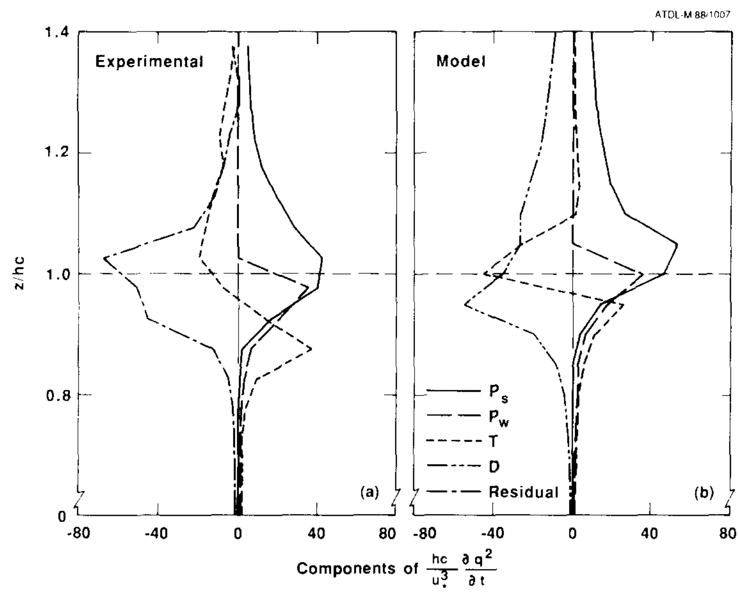

Fig. 6. Experimental and modeled components of terms in the turbulent kinetic energy (TKE) budget. P_s is shear production, P_w is wake production, T is turbulent transport, D is the dissipation rate and pressure transport from the model which is to be compared with the residual from the experimental analysis.

surface layer flows (Kaimal et al., 1972). The extracted large-scale shear kinetic energy (SKE) and MKE should reappear at higher frequencies as the energy (neglecting inertial losses) under the power spectrum is usually conserved. However, since the sonic anemometers used in this experiment have a finite average path (20 cm), the expected energy increase at the higher frequencies could not be resolved.

In past applications of higher-order closure models to flow in plant canopies, the rate at which wake turbulence is generated is balanced by the dissipation rate, which tends to increase the levels of the velocity variances. Following the framework discussed by Shaw and Seginer (1985), Wilson (1988) split the TKE into two frequency bands. The low-frequency band is associated with turbulent SKE and the high-frequency band is comprised of motions associated with wake kinetic energy (WKE). The equations were then derived to account for the transfer of TKE into and out of each frequency band. The advantage of this approach is that the dissipation of wake-generated turbulence is not a function of the velocity variances. Wilson (1988) found that this dual-frequency band model gave reasonably good predictions of the mean wind and velocity variances in two different canopies.

The transport term is the major source of TKE from $z/h_c = 0.9$ to 0.6. The model overestimates the loss of TKE through transport near the top of the canopy and underpredicts the net import of TKE below this region. Also, the model predicts the peak net source of TKE at a higher level than is observed in the transport profile derived from measurements. This results from the modeled third-order moment profiles peaking at a higher level than the measured values (see Fig. 5), which may be due to the application of the quasi-Gaussian assumption. From Fig. 5, the measured gradients of the triple velocity products are steeper than those from the model, hence a stronger source of TKE from turbulent transport is observed.

The vertical profiles of shear production (P_s) and transport (T) of TKE agree reasonably well with the measurements of Lesnik (1974) for a pine forest. Also found are several similarities in the structure of the components of TKE when compared to the numerical results of Wilson and Shaw (1977) for corn, Meyers and Paw U (1987) for soybeans, Raupach et al. (1987) for an artificial canopy and Shi et al. (1987) for a deciduous forest in Canada. In all cases, P_w exceeds P_s at all levels except near the top of the canopy. The transport term is also the major source of TKE below the bulk of the plant canopy elements. Because so much of the leaf area for the deciduous forest is contained in the top few meters of the canopy, the gradients are nearly constant below $z/h_c=0.75$ (Fig. 6), although in the crop and artificial canopy appreciable gradients exist at $z/h_c=0.3$. The vertical distribution and associated drag of the canopy elements play a major role in determining the turbulence structure.

Tangential stress budget

Figure 7 shows the vertical distribution of the terms in the shear stress ($\overline{u'w'}$) budget equation. Above the canopy, it is generally observed that for neutral conditions, equilibrium exists between the production rate of stress due to interactions with the mean wind field (eqn. 2, Term Ib) and the rate of loss through the pressure–velocity term (eqn. 2, terms IIIb), with a minor contribution from the turbulent transport term (IIb). Below the top of the canopy, the transport term is significant and is an important source of tangential stress near $z/h_c=0.9$. In the modeled results, the turbulent transport term generally shows a smaller contribution. This result is expected from an examination of the measured and modeled $\overline{w'^2u'}$ profiles (Fig. 5d). As with the TKE budget, the components attain a relatively constant value at $z/h_c=0.75$. Again, this result is due to the majority of the leaves being within the top few meters of the canopy extracting most of the available momentum. The relative contributions of the components in tangential stress budget are not really discernable below $z/h_c=0.7$, and the role of the turbulent transport term in maintaining the counter-gradient flux structure for the mean wind profile cannot be assessed. Overall, the measured and modeled tangential stress budgets are in good general agreement.

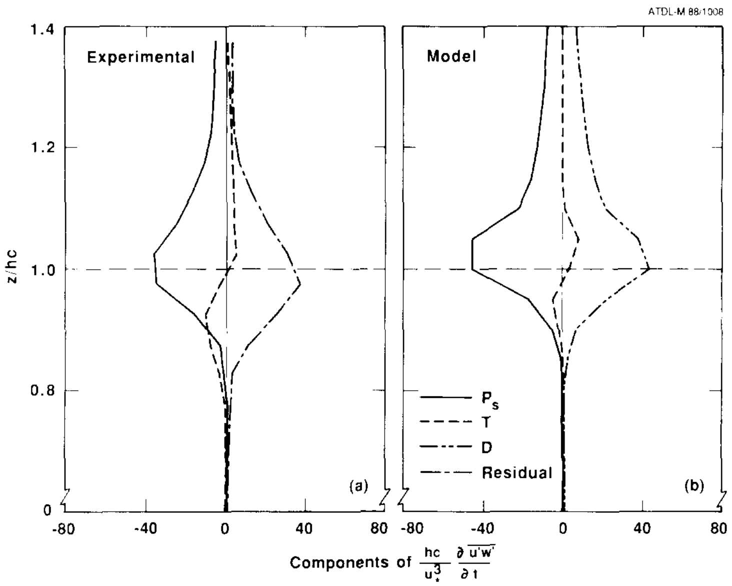

Fig. 7. Experimental and modeled components of tangential shear stress budget. P_s is the shear production, T is the turbulent transport and D is the pressure destruction which is to be compared with the residual from the experimental analysis.

CONCLUSIONS

In comparisons of the data here to results from other studies, the plant canopy architecture is found to play a major role in determining the turbulence structure within plant canopies. Experimental investigations of canopy turbulence processes need to assess the vertical distribution of leaf area to aid in the interpretation of turbulence data within plant canopies.

The architecture of the deciduous forest in this study yields a turbulence structure that is similar to that found in a tropical forest. This is not surprising since the canopies of the tropical and deciduous forests resemble each other. These forests typically have the majority of leaf area in the upper third of the canopy, which is associated with large gradients of first-, second- and third-order velocity moments. Below this level, the gradients practically vanish, but the transport terms in the second-order budget equations are believed to sustain the levels of mean wind and turbulence found in the trunk space.

The higher-order closure model overestimated the TKE components in the upper canopy and underestimated them in the lower canopy, even though the mean wind profile is well predicted. As a result of this, the triple velocity moments and the corresponding contribution of the transport terms in the second-order budget equations are underestimated. The overprediction of the TKE components in the upper canopy is probably a result of the parameterization of the dissipation rate of TKE. Although the wake production of TKE exceeds gradient production, the scales of motion in the wakes probably do not significantly contribute to the velocity variances. However, the parameterized rate of dissipation is proportional to q^3, forcing the wake-generated TKE to reappear in the form of the velocity variances. A first step towards better predictions of velocity variances within the canopy was made by Wilson (1988) by using a dual-frequency closure model which separately determines the low-frequency SKE and the WKE which has a minor contribution to the variance.

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