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THE EFFECTS OF EXTREME TURBULENT EVENTS ON THE ESTIMATION OF AERODYNAMIC VARIABLES IN A DECIDUOUS FOREST CANOPY

DENNIS D. BALDOCCHI and TILDEN P. MEYERS

Atmospheric Turbulence and Diffusion Division, NOAA/ARL, P.O. Box 2456, Oak Ridge, TN 37831 (U.S.A.)

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ABSTRACT

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Heat, mass and momentum transfer, and the turbulence regime within a plant canopy, are dependent upon aerodynamic variables which are non-linearly related to wind speed. Measurements made in plant canopies show that turbulence is intermittent and non-Gaussian. Therefore, a statistical question arises when evaluating non-linear wind speed-dependent, aerodynamic variables: is the mean value of an aerodynamic function equal to that function evaluated at the mean wind speed? We evaluated the above-stated, statistical question for boundary layer resistances to mass and momentum transfer, the form drag force and the rate of work against form drag. Pertinent computations were based upon turbulence measurements made within a fully leafed, deciduous forest. In addition, expected values of these aerodynamic variables were computed with probability density functions derived from the Gram-Charlier expansion series.

Boundary layer resistances for water vapor (R_b) and momentum (R_m), computed with mean wind speeds, underestimate mean functional values by 5-20%. On the other hand, estimates of R_b and R_m derived from probability density functions underestimate mean functional values by < 3%. Computations of the form drag force, based on probability density functions and mean wind speeds, respectively, overestimate and underestimate mean functional values by ~ 20%. Theoretically, the form drag force in the streamwise direction is a function of the product of the horizontal wind velocity and the scalar wind speed. Hence, parameterizing its value based only on scalar wind speed squared is apt to be error prone. Estimates of the rate of work against form drag, based on the probability density functions, agree within 5% of mean functional values. The rate of work against form drag computed on the basis of the mean horizontal wind speed cubed underestimates mean functional values by 30-60%. This underestimate, however, is expected since it represents the rate of work done by the mean wind, which is a different quantity.

INTRODUCTION

When mass, heat and momentum are transferred between the free-stream atmosphere and a leaf surface, molecules must diffuse through the viscous sublayer in contact with the surface of the leaf. The thickness of this boundary layer, and hence its resistance to mass, heat and momentum transfer, are non-linear functions of wind speed (see Schlichting, 1968).

The vertical profiles of mean wind speed and its variance within a plant canopy result from interactions between wind and plant elements. The plant–wind interactions include form drag forces, which absorb momentum (Raupach and Thom, 1981), and the rate of work against form drag, which converts kinetic energy of the mean flow and the shear-generated, turbulence into kinetic energy of wake-produced turbulence (Raupach and Shaw, 1982; Shaw and Seginer, 1985; Wilson, 1988). Both form drag forces and the rate of work against the form drag are non-linear functions of wind speed. The form drag force is approximated as a function of wind speed squared and the rate of work against form drag is a function of wind speed cubed (Shaw, 1982; Shaw and Seginer, 1985),

The growing literature on turbulence in plant canopies shows that the wind speed regime inside many different plant canopies varies with height and that the turbulence regime is very intermittent, and the probability distributions of the velocities are non-Gaussian (Shaw et al., 1979; Wilson et al., 1982; Shaw and McCartney, 1985; Baldocchi and Hutchison, 1987; Baldocchi and Meyers, 1988a). The statistical question that arises when evaluating the above-mentioned, aerodynamic variables is whether the mean value of a wind speed-dependent function is equal to the function evaluated at the mean wind speed?

The objective of this paper is to evaluate the errors in estimating non-linear, wind speed-dependent aerodynamic functions, related to mass, heat and momentum transfer, and the turbulent kinetic energy budget. These aerodynamic functions include the boundary layer resistances to mass, heat and momentum transfer, form drag forces and the rate of work against form drag. Estimates of mean values of the said aerodynamic variables are computed as functions of mean wind speed and with probability frequency distributions. Errors are evaluated by comparing these computations against mean functional values determined from time series of instantaneous wind speeds that were measured in a deciduous forest.

MATERIALS AND METHODS

Experiment

Three-dimensional, wind velocity components were measured in a fully leafed, deciduous forest during September and October, 1986. The forest had a leaf area index of ~ 4.9 and the average height of the stand was ~ 23 m. The forest stand is situated on a ridge in moderately sloping terrain and is located near Oak Ridge, TN. A detailed description of the architectural characteristics of the forest stand is given in Hutchison et al. (1986). Wind speeds were measured inside the forest with three-dimensional, sonic anemometers. Turbulence measurements at a reference level above the canopy were made with a Gill *uvw* propeller anemometer. Data were acquired and digitized at a rate of 7.6 Hz with a computer-controlled data acquisition system. A full description of this experiment and the instrumentation are provided in Baldocchi and Meyers (1988a, b).

Computations

Mean functional values were evaluated from time series of wind speed (U) measurements made inside the forest canopy

$$\overline{f(U)} = 1/T\int_0^T f(U(t))\mathrm{d}t \tag{1}$$

where $f(U)$denotes a functional operation on U, the overbar represents time averaging and T is the length of the time series. Instantaneous wind speed (U) is a function of the three orthogonal wind velocity components u, v and w which lie in the x, y and z directions, respectively

$$U = (u^2+v^2+w^2)^{1/2} \tag{2}$$

A sampled population consists of discrete values (x) distributed about a mean. If the population frequency distribution can be accurately characterized in terms of a probability density function ($p(x)$), the expected value of a function represents the mean and is expressed as

$$\mathrm{E}[f(X)] = \int_{-\infty}^{\infty} f(x)p(x)\mathrm{dx} \tag{3}$$

where the upper case X denotes a random variable and the lower case x denotes particular values that occur in the population of X (Mendenhall and Scheaffer, 1973). The probability density function is defined such that all values of $p(x)$ are bounded between 0 and 1, and the integral of $p(x)$ between infinity and minus infinity equals one.

When the probability distribution for some measured quantity is not normal or Gaussian, an approximate probability density function can be derived based on the higher derivatives of the Gaussian distribution (see von Mises, 1964). This distribution is often denoted as the Gram–Charlier series. The Gram–Charlier series has been previously applied in turbulence to compute kurtosis of velocity gradients (Takeuchi, 1979).

Gram–Charlier probability density function, normalized on the basis of a zero mean and a variance of one, is defined as

$$p_{GC}(x)=1/(\sqrt{2\pi})^{1/2}\exp(-x^2/2)\ [1+Sk\ (x^3-3x)/6 + (Kr-3)\ (x^4-6x^2+3)/24] \quad (4)$$

Sk is skewness (the third moment) and is defined as $\overline{x'^3}/\sigma_x^3$; Kr is kurtosis (the fourth moment) and is defined as $\overline{x'^4}/\sigma_x^4$. The standard deviation of x is denoted: σ_x. When the probability frequency distribution is Gaussian, skewness equals zero, kurtosis equals three and eq. 4 reduces to the Gaussian probability density function.

We numerically evaluated the expected value of a wind speed-dependent function ($\mathrm{E}[f(U)]$) using the probability density function, shown in eq. 4, and by transforming $f(x)$ into $f(U)$

$$\mathrm{E}[f(U)]=\sum_x f(\overline{U}+x\sigma_u)\ p_{GC}\ (x)\ \Delta x \quad (5)$$

The summation in eq. 5 was performed in the range between plus and minus four standard deviations of the mean, on 0.1 intervals (Δx).

RESULTS AND DISCUSSION

Mean wind statistics

Mean wind speed statistics are presented below to demonstrate that turbulence is non-Gaussian in a deciduous forest canopy and to show its vertical variability. Data from between 12 and 40 half-hour measurement periods were used to compute the following turbulence statistics.

The mean wind speed regime, normalized by friction velocity measured above the canopy, is characterized by a region of strong shear in the upper 20% of the canopy, followed by a secondary wind speed maxima at $\sim 0.46h$ (h is canopy height), and a subsequent decrease with the approach of the canopy floor (Fig. 1). The features of this profile resemble those for the u wind velocity component (see Baldocchi and Meyers, 1988a). The level of great shear occurs in a higher region of the canopy than is commonly observed in agricultural crops (see Meyers and Paw U, 1986). In this forest canopy, most of the form drag against the mean wind, and hence the mean wind shear, occurs near the canopy–atmosphere interface since > 75% of the leaf area occurs in the upper 25% of the canopy (see Hutchison et al., 1986).

Turbulence levels inside the forest canopy are relatively high (Fig. 2). The mean turbulence intensities of U ($\sigma_U/\overline{U}$) inside the canopy range between 0.3 and 0.6, and are generally greater than values measured in the surface layer above the canopy. On the other hand, the magnitude of these turbulence intensities are smaller than those associated with the individual wind vector components measured in this forest canopy (Baldocchi and Meyers, 1988a).

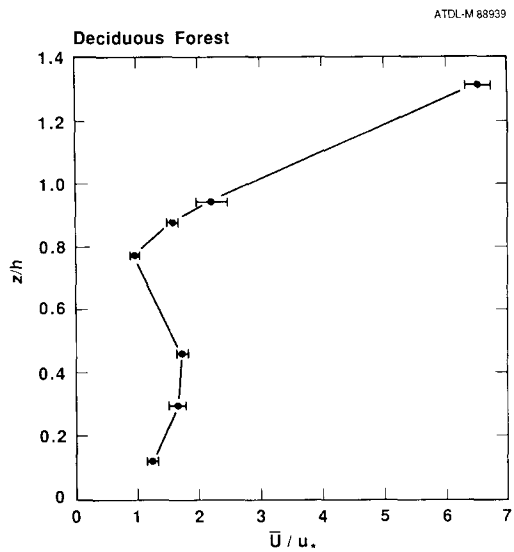

Fig. 1. Vertical profile of mean scalar wind speed above and within a deciduous forest canopy. These values are normalized by friction velocity (u^*) measured above the canopy.

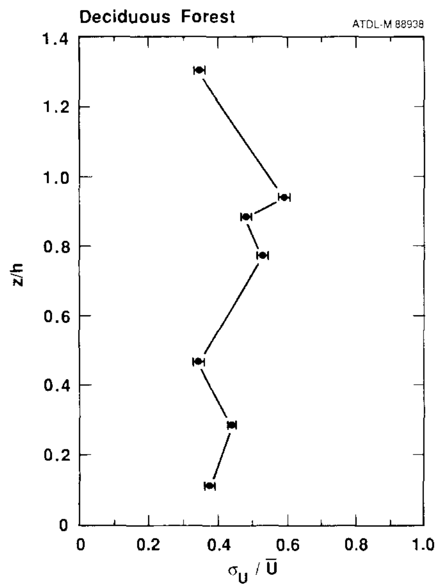

Fig. 2. Vertical profile of the mean scalar wind speed turbulence intensity measured above and within a deciduous forest canopy.

Vertical air movement makes a sizeable contribution to the wind speed regime in a fully leafed deciduous forest. Thereby, the magnitude of the denominator, $\overline{U}$, that is used to compute these turbulence intensities is greater than the denominator, $\bar{u}$, that was used to compute the turbulence intensities for the individual wind vector components (Baldocchi and Meyers, 1988a). The wind speed turbulence intensities ($\sigma_U/\overline{U}$) are also slightly smaller than those for horizontal wind speed measured in a mixed deciduous forest range (Cionco, 1972), which range between ~ 0.6 and 0.8.

Turbulence intensities are greatest near the top of the canopy and then gradually decrease with depth. The greatest values occur at the canopy–atmosphere interface because it is in this region where shear production of turbulent kinetic energy (TKE) is greatest (Meyers and Baldocchi, 1988). Although peak wake production occurs lower in the crown, it is not associated with a sizeable increase in turbulence intensity. Work against form drag generates turbulent wakes behind plant elements, which have length scales much smaller than those of shear-produced, turbulent kinetic energy. Although the production rates of shear- and wake-produced turbulent kinetic energy are similar, the smaller scale, wake-generated TKE dissipates much faster than the larger scale, shear-produced TKE and does not contribute greatly to the measurable turbulence variance (Raupach and Shaw, 1982; Shaw and Seginer, 1985).

Skewness values are significantly greater than zero, indicating that the probability frequency distribution is not Gaussian and that turbulent events are skewed towards the occurrence of large wind gusts (Fig. 3). Greatest skewness values are of the order of 1.7 and occur near the top of the canopy. Wind speed in a plant canopy is positively skewed because intermittent sweeps of fast moving air from above penetrate into the canopy, whereas there is no offsetting source of air slower than the mean (Shaw and Seginer, 1987). Above the canopy, skewness is still positive, yet it is relatively small, ~ 0.16.

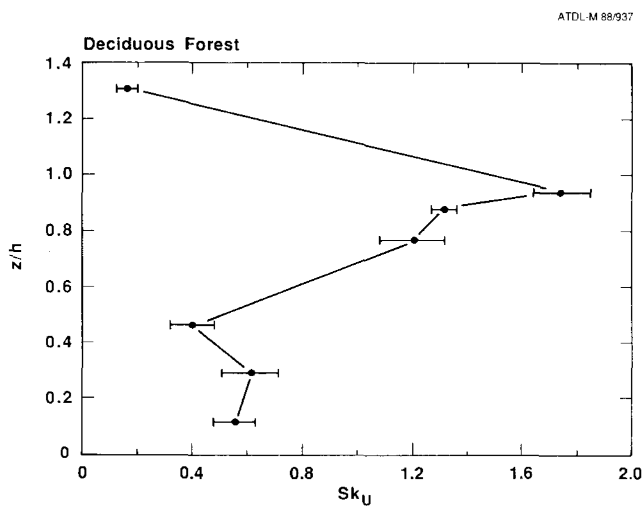

Fig. 3. Vertical profile of the mean scalar wind speed skewness statistic, measured above and within a deciduous forest canopy.

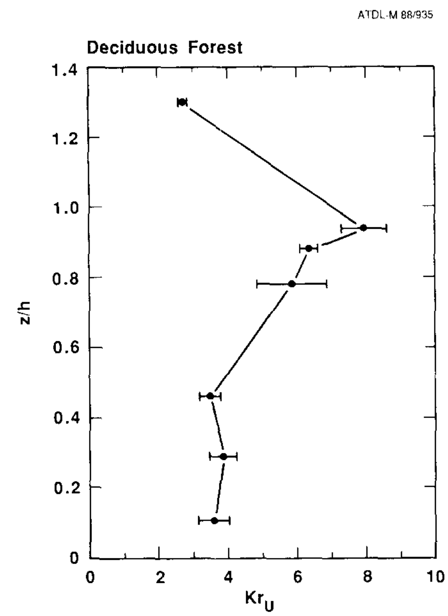

Fig. 4. Vertical profile of the mean scalar wind speed kurtosis statistic measured above and within a deciduous forest canopy.

The skewness values observed inside the canopy agree relatively well with values for the *u* vector measured in corn (Shaw and Seginer, 1987). However, our values are not as great as those reported for scalar wind speed measured in sorghum and barley (Shaw and McCartney, 1985), which were as large as 3.0.

Kurtosis values also reach a maximum near the top of the canopy and decrease with depth into the canopy (Fig. 4). The maximum values are of the order of 8, further supporting the contention that turbulence inside a deciduous forest canopy is not Gaussian. Yet, these values are also smaller than those measured in barley and sorghum, which reach 20 (Shaw and McCartney, 1985).

Probability density functions

We propose using the Gram–Charlier expansion series to simulate probability density functions (PDFs) for wind speeds measured inside a deciduous forest canopy since we have demonstrated that turbulence in this canopy is non-Gaussian. The success of using the Gram–Charlier expansion series to compute the probability density function's wind speed inside the forest canopy is shown in Fig. 5(a)–(f). This expansion series simulates the PDFs for wind speed measurements reasonably well. The best agreement between measured and computed values is associated with measurements made below crown clo-

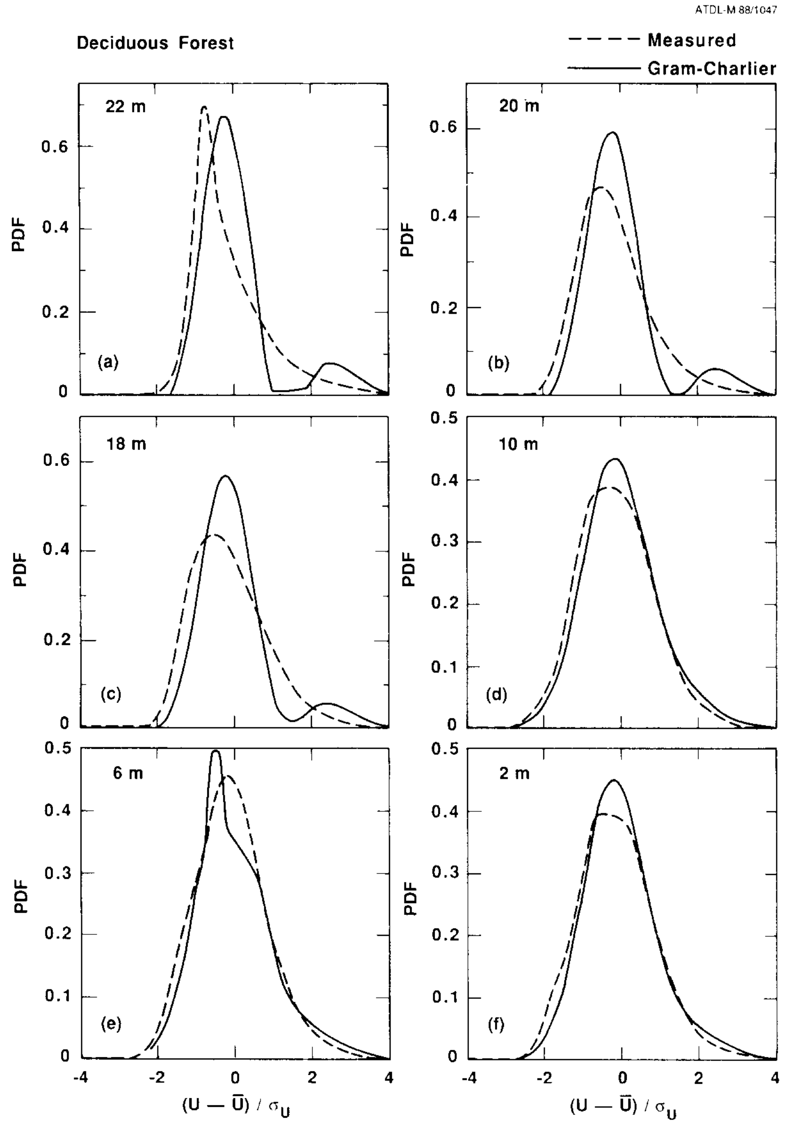

Fig. 5. The mean probability frequency distributions of scalar wind speed. Values are based on measurements and computations using the Gram-Charlier expansion series.

sure (Fig. 5(d), (e) and (f)), where the frequency distribution of wind speed events is less skewed and kurtotic (see Figs. 3 and 4). The computed frequency distributions for wind speeds in the canopy crown (Fig. 5(a), (b) and (c)) are bimodal, with a small second peak occurring at normalized values ranging between 2 and 4. This bimodality does not represent the frequency distributions of wind speeds measured in the plant canopy, which are unimodal. The computed bimodal frequency distribution results from a great contribution of the terms in eq. 4 that are associated with the skewness (Sk) and kurtosis (Kr), since the magnitudes of Sk and Kr are large in the canopy crown (Figs. 3 and 4). The skewness and kurtosis terms are based on the third and fourth derivatives of the Gaussian distribution. The frequency distribution of these derivatives have lobes that are not centered about the mean (see von Mises, 1964, p. 135) and, hence, contribute to the computation of a bimodal probability frequency distribution under strongly skewed and highly kurtotic conditions.

Shaw et al. (1979) have applied other probability density functions to simulate the frequency distribution of within-canopy, wind speed measurements. They tested the γ, Weilbull and extreme value distributions, and found that these distributions simulated data near the mean well, but failed to capture the extreme wind events.

Boundary layer resistances

A resistance-analog expression is often used to calculate fluxes of mass (F_c), sensible heat (H) and momentum (τ) to and from leaves in plant canopies.

$$F_c = -\rho_a[c(z) - c(0)]/(R_b + R_s) \tag{6}$$

$$H = -\rho_a C_p (T_a - T_s)/R_h \tag{7}$$

$$\tau = -\rho_a \mathrm{U}/\mathrm{R_m} \tag{8}$$

where c is the mixing ratio of a particular scalar, ρ_a is air density, C_p is the specific heat of air, R_s is the surface resistance, R_h is the heat resistance, T is the respective temperature at the leaf surface (s) and in the free-stream air (a), and U is wind speed.

R_b is the boundary layer resistance for mass transfer and is expressed as

$$R_b = l/D_x Sh \tag{9}$$

where l is the characteristic length of the leaf, D_x is the molecular diffusivity for the entity x and Sh is the Sherwood number. The Sherwood number is computed on the assumption that mass transfer over a leaf is analogous to transfer over a flat plate (Campbell, 1977; Grace, 1980). From engineering theory, Sh can be parameterized as

$$Sh = 0.66\, Re^{0.5}\, Sc^{0.33} \text{ for laminar flow} \tag{10a}$$

$$Sh = 0.037\, Re^{0.8}\, Sc^{0.33} \text{ for turbulent flow} \tag{10b}$$

The Schmidt number (Sc) is defined as ν/D_x and the Reynold's number (Re) is defined as $l\,U/\nu$, where ν is kinematic viscosity. Experimental work by Grace and Wilson (1976) shows that flat plate theory underestimates the Sherwood number measured over real leaves by a factor of two due to leaf flutter, a mixed regime of turbulent and laminar flow over a leaf, natural variations in leaf size and variations in the transition distance over a leaf. For the computations discussed below, we compute Sh using eq. 10 and by multiplying the product by a factor of two.

The vertical variation in the mean value of the boundary layer resistance to water vapor transfer and its estimates are shown in Fig. 6 (a). These values are normalized by mean friction velocity (u_*) measured above the canopy. The shapes of the normalized R_b profiles are a mirror image of the mean normalized wind speed profile – the greatest resistance to water vapor transfer occurs where wind speeds are at a minima. The relative errors in computing normalized R_b values, based on the schemes discussed above, are shown in Fig. 6 (b). Expected values of R_b, derived from the PDFs, underestimate mean values derived from instantaneous field measurements of U by $<3\%$. On the other hand, compu-

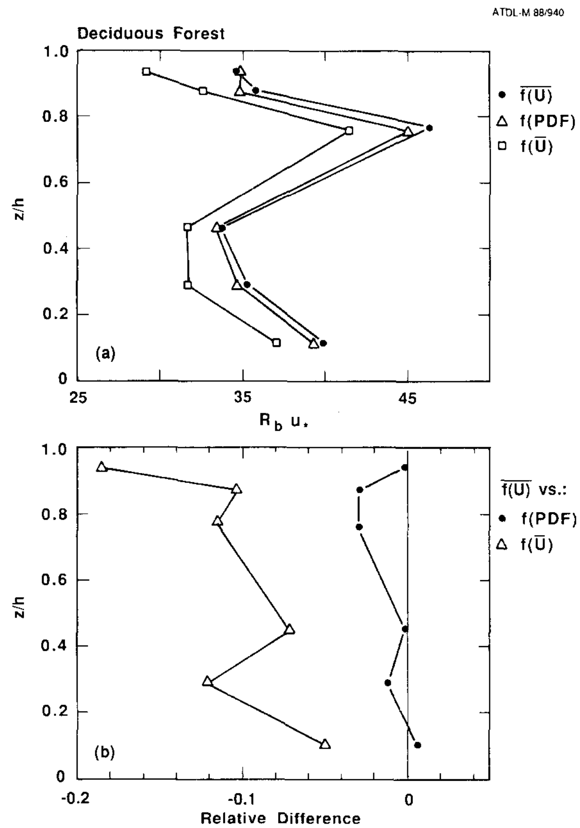

Fig. 6. (a) Vertical profile of the boundary resistance for water vapor transfer non-dimensionalized by friction velocity (u_*). The expected value of $R_b u_*$ [$\overline{f(U)}$] is compared against estimates derived from the mean wind speed [$f(\bar{U})$] and the Gram-Charlier probability density function [$f(PDF)$]. (b) The relative error in the computation of $R_b u_*$.

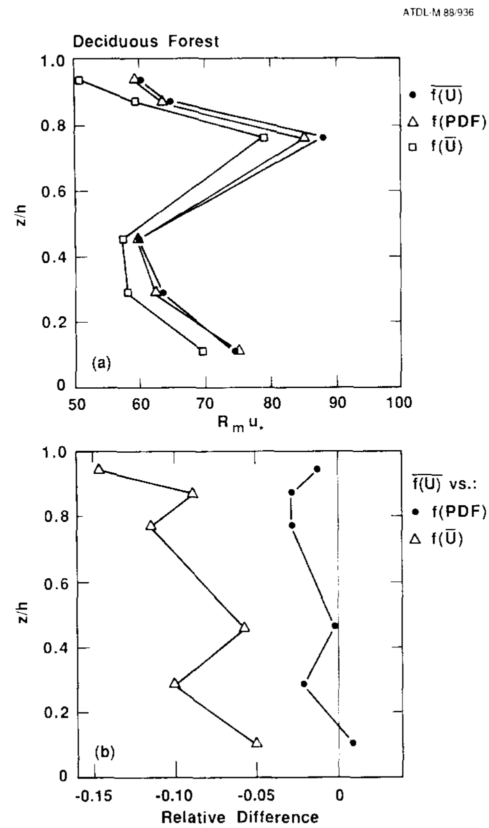

Fig. 7. (a) Vertical profile of the boundary layer resistance for momentum transfer non-dimensionalized by friction velocity (u_*). The expected value of $R_m u_*$ [$\overline{f(U)}$] is compared against estimates derived from the mean wind speed [$f(\bar{U})$] and the Gram-Charlier probability density function [f(PDF)]. (b) The relative error in the computation of $R_m u_*$.

tations of R_b derived from mean wind speeds underestimate the mean functional values by 5–19%.

To compute the resistance to heat transfer, R_h, the Schmidt number in eq. 10 is replaced with the Prandtl number (Pr), which is the ratio between kinematic viscosity and thermal diffusivity, and this substitution transforms the Sherwood number into the Nusselt number (Nu). The magnitude and relative errors in computing R_h, with either the probability density functions or mean wind speeds, will differ from values of R_b (Fig. 6) in proportion to the ratio, Pr/Sc.

The boundary layer resistance to momentum transferred via skin friction is expressed as

$$R_m = \text{constant}(l/U)^{1/2} \tag{11}$$

A typical value for the constant is 388 (Campbell, 1977).

Figure 7(a) shows the vertical profiles for the boundary layer resistance for momentum transfer (R_m), normalized by u^*. The shapes of the normalized, vertical profiles of R_m resemble those for R_b. However the magnitudes of R_m are about twice those of R_b at corresponding levels. The mean values of R_m are compared against estimates that are computed with the PDFs and mean wind speeds in Fig. 7(b). Momentum transfer resistances based on the PDFs generally underestimate mean functional values of R_m by $<3\%$, whereas values of R_m derived from mean wind speed measurements underestimate mean functional values of R_m by 5–15%.

Turbulence

Turbulence structure in a plant canopy can be estimated by simultaneously solving the budget equations for mean, horizontal wind velocity ($\bar{u}$), tangential shear stress ($\overline{w'u'}$) and turbulent kinetic energy ($\overline{q'^2}=\overline{u'^2}+\overline{v'^2}+\overline{w'^2}$) by incorporating a higher order closure scheme (Wilson and Shaw, 1977; Meyers and Paw U, 1986; Wilson, 1988). Some of these budget equations are parameterized using non-linear, wind speed-dependent functions. For this analysis, we will concentrate on the form drag force, a component of the tangential shear stress budget, and the rate of work against form drag, a component of the turbulent kinetic energy budget.

Form drag force

The mean form drag force per unit volume on a collection of leaves at an arbitrary level in a plant canopy is a function of wind speed squared (Shaw, 1982; Shaw and Seginer, 1985)

$$F_d(z)=\rho_a C_d a(z)\overline{U(z)^2} \tag{12}$$

where C_d is the effective drag coefficient and $a(z)$ is leaf area density.

In a horizontally homogeneous, extended canopy, under steady state conditions, the budget equation for the horizontal wind velocity reduces to a balance between the flux divergence of tangential shear stress and the mean form drag force in the direction of the mean wind (Shaw, 1982)

$$\partial\overline{w'u'}/\partial z=-C_d a(z)\overline{u(z)U(z)} \tag{13}$$

where the primes represent fluctuations from the temporal mean. Due to the unavailability of proper wind statistics, the form drag force term in eq. 13 is generally parameterized in terms of eq. 12 (Shaw, 1982) or the mean horizontal wind velocity squared (Wilson and Shaw, 1977; Meyers and Paw U, 1986).

Figure 8(a) shows the vertical profiles of the mean value of canopy form drag force and its estimates, normalized by u_*^2. We assume C_d equals 0.2 and $a(z)$ is obtained from measurements reported in Hutchison et al. (1986). The

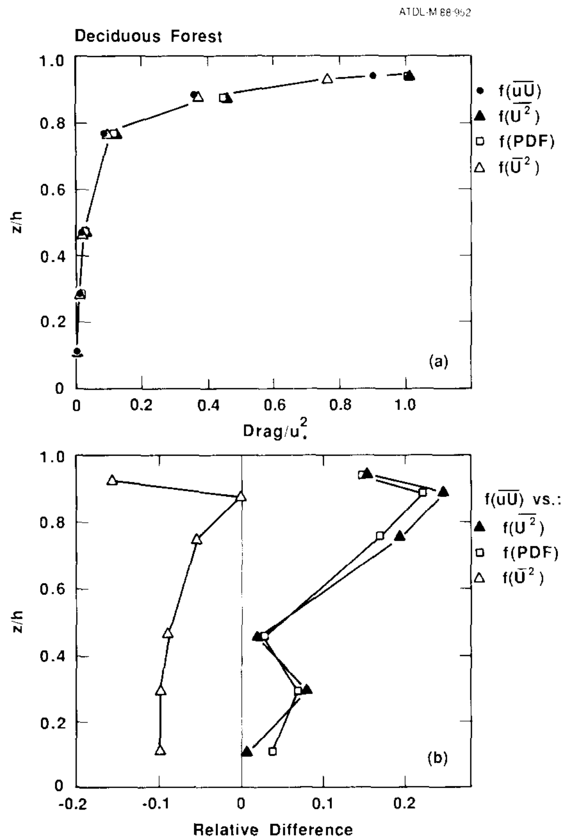

Fig. 8. (a) Vertical profile of the mean form drag force, normalized by u_*^2. The expected value of the form drag force $[f(\overline{uU})]$ is compared against estimates derived from $f(\overline{U^2})$ the mean wind speed $[f(\bar{U})]$ and the Gram-Charlier probability density function $[f(\text{PDF})]$. (b) The relative error in the computation of mean normalized form drag force.

normalized drag profile shows strong curvature. Values of normalized drag decrease with depth from 1.0 to $\sim$ 0.006.

The relative errors associated with estimating eq. 13 on the basis of $\overline{U^2}$, the PDF of U and the mean wind speed squared $(\bar{U}^2)$ are shown in Fig. 8(b). In the upper portion of the canopy, where turbulence is great and intermittent, the estimates of form drag force, based on $\overline{U^2}$ (eq. 12) and the PDFs, overestimate the mean functional values (eq. 13) by 14–25%. On the other hand, estimates of form drag force, based on the mean wind speed squared, underestimate the actual values by as much as 16%. Below crown closure, the errors associated in estimating form drag force with the three described methods diminish and are typically $<10\%$ since turbulence is less skewed and kurtotic in this region.

Estimates of the form drag force, based on the PDFs, agree quite well with the estimate of the drag force based on eq. 12. This agreement illustrates the need to account for extreme wind events when evaluating this non-linear function. On the other hand, an underestimate, as large as 30%, can occur by evaluating eq. 12 as a function of the mean wind speed squared, since the extreme wind events are not properly considered.

Work against form drag

The turbulent kinetic energy (TKE) budget provides the framework for examining the processes that contribute to the production, transfer and removal of turbulent fluctuations. Inside a plant canopy, TKE is produced via mean wind shear and by the rate work done by the velocity fluctuations against form drag forces (W) (see Raupach and Shaw, 1982; Shaw and Seginer, 1985; Wilson, 1988). The steady-state TKE budget for shear-produced turbulence in a horizontally homogeneous canopy under adiabatic conditions is

$$\tfrac{1}{2}\partial\overline{q'^2}/\partial t = 0 = -\overline{u'w'}\,\partial\bar{u}/\partial z - \partial[\tfrac{1}{2}\overline{q'^2w'} + \overline{p'w'}]/\partial z - W - \epsilon_s \tag{14}$$

where $\overline{q'^2} = \overline{u'^2} + \overline{v'^2} + \overline{w'^2}$, p is static kinematic pressure and ϵ_s is the dissipation rate of shear-produced turbulence.

In order to evaluate the TKE budget in plant canopy, we must properly evaluate W. Shaw and Seginer (1985) show that the rate work is done by velocity fluctuations against form drag, which also represents the rate of conversion of large-scale, shear-produced TKE into smaller scaled, wake-produced TKE

$$W = C_d a(z)[\overline{U^3} - \bar{u}\,\overline{uU}] \tag{15}$$

Equation 15 represents the difference between the rate mean work done against form drag

$$\hat{W} = C_d a(z)\overline{U^3} \tag{16}$$

and the rate of work done by the mean flow

$$\overline{W} = C_d a(z)\bar{u}\,\overline{uU} \tag{17}$$

Since eq. 16 is a function of wind speed cubed, what is the magnitude of the error which arises due to evaluating this equation in terms of the probability density functions or mean wind speed cubed?

Figure 9(a) shows the vertical profile of the rate of mean work against form drag (eq. 16) and its estimates, normalized by u_*^3. The rate of mean work against form drag is great near the top of the canopy, where turbulence and plant area density are greatest. At lower levels in the canopy, values of normalized work are relatively insignificant since little leaf area resides in the lower canopy. The substantial rates of work in the upper canopy support our observation that work against form drag reduces the scales of turbulence and

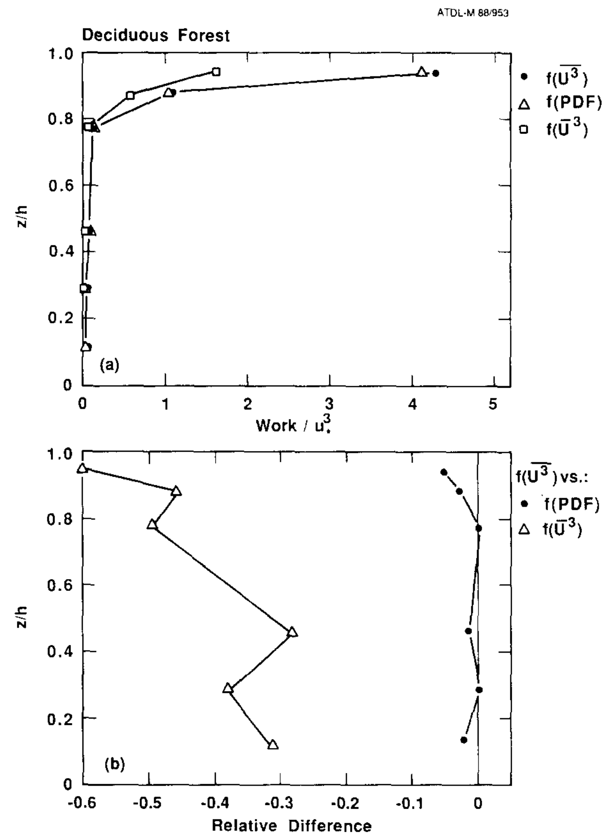

Fig. 9. (a) Vertical profile of the rate of mean work against form drag, normalized by u_*^3. The expected value of the work term $[\overline{f(U)}]$ is compared against estimates derived from the mean wind speed $[f(\bar{U})]$ and the Gram–Charlier probability density function [f(PDF)]. (b) The relative error in the computation of normalized mean work.

short-circuits the inertial cascade of turbulent kinetic energy (Baldocchi and Meyers, 1988b).

Figure 9 (b) shows that estimates of the rate of mean work against form drag, derived from the Gram–Charlier PDFs, underestimate mean functional values by <5%. Since the rate of work is a function of wind speed cubed, evaluating the mean value of this function will be weighted towards the extreme events. Consequently, any improvement in estimating the probability of these extreme events will lead to an improved estimate of the expected value of that function. Furthermore, it is not correct to parameterize the expected value of the rate mean work against form drag (eq. 16) in terms of $\bar{U}^3$ since these two functions differ by 28–62%.

DISCUSSION AND SUMMARY

Extreme turbulent events occur with enough frequency to influence the estimate of non-linear, wind speed-dependent variables inside a forest canopy. We find that considerable improvement is made by estimating boundary layer resistances and the rates of work against form drag in a deciduous forest using PDFs derived from higher order statistical moments. PDFs, computed with the Gram–Charlier expansion series, exhibit spurious second peaks (Fig. 5). This bimodality, however, does not result in significant errors in the computation of the mean functional value of the boundary layer resistances for water vapor and momentum transfer due to skin friction and the rates of work against form drag. The agreement between the mean functional values and the expected values derived from the PDFs are often within 3%.

The errors introduced by estimating R_b, R_h and R_m using mean wind speeds will contribute appreciably to errors in the estimates of nitric acid vapor (HNO_3), heat and momentum transfer due to skin friction since the transfer of these entities is inversely related to their respective resistance. On the other hand, errors due to estimating the boundary layer resistance to mass transfer with mean wind speeds will contribute less to errors in the calculation of exchanges rates of chemical species with strong surface resistances since the boundary layer resistance is often much smaller than its companion surface resistance.

The form drag force is a function of $\overline{uU}$ instead of $\overline{U^2}$. Consequently, use of the probability density functions for U does not improve upon the estimate of the mean form drag force. Others (Wilson and Shaw, 1977; Meyers and Paw U, 1986) compute the form drag force in terms of the mean horizontal wind velocity squared. However, this formulation is also incorrect and can also result in sizeable errors. Although, these authors have reported good agreement between predicted and measured wind velocity profiles in plant canopies, their favorable results may arise from optimizing the canopy drag coefficient, which offsets the error in parameterizing the form drag force in terms of $\bar{u}^2$.

It is most critical to account for extreme turbulent events when estimating the rate of mean work against form drag since this variable is a function of U cubed. Although PDFs computed with the Gram–Charlier distribution do not perfectly mimic measured wind speed frequency distributions, use of the synthetic PDFs greatly improves upon the estimate of $\hat{W}$. This information should be incorporated into higher order closure modeling schemes that estimate the rate of conversion of shear-produced turbulent kinetic energy to wake-produced turbulent kinetic energy (e.g., Wilson, 1988).

Turbulence statistics in plant canopies vary widely, depending upon the canopy structure. The errors that occur in estimating aerodynamic variables will depend on skewness and kurtosis of wind speed that result from the plant canopy–wind interactions.

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