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Effects of canopy morphology and thermal stability on mean flow and turbulence statistics observed inside a mixed hardwood forest

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ABSTRACT

The influences of thermal stability and seasonal changes in canopy morphology on mean flow and turbulence statistics in a mixed hardwood forest are presented from a year long field experiment at the University of Michigan Biological Station AmeriFlux site. A secondary wind speed maximum at $z/h = 0.07$ (z is height above ground and h is mean canopy height) below the level of peak vegetation area density (VAD) in the understory (young white pines) is observed more frequently and is more pronounced in fully leafed (closed) canopy than defoliated (open) canopy, and in stable than near-neutral and unstable conditions. A secondary wind speed maximum at $z/h = 0.58$ is observed only in the closed canopy below the level of peak VAD in the upper canopy (crowns of mature aspen trees), which occurs less frequently and is less pronounced than that at $z/h = 0.07$. Horizontal mean winds in the forest are observed to flow to the left (counter-clockwise) of that at the canopy top. The degrees of turning of the mean winds increase with increasing depth into the forest except a reversal (clockwise) near the forest floor in the closed canopy. The degrees of turning are greater in the closed canopy than the open canopy but smaller in near-neutral than unstable and stable conditions. The attenuations of Reynolds stress, correlation coefficient and velocity variances with increasing depth into the forest are more rapid in the closed canopy and in stable conditions. But the relative turbulence intensities are greater in the closed canopy than in the open canopy and decrease with increasing stability. In near-neutral stability, the zero-plane displacement height (d) for the closed canopy decreases with increasing wind speed ($\sim 0.81h$ on average), while d for the open canopy does not show a clear dependence on wind speed ($\sim 0.65h$ on average). The bulk drag coefficient (C_D^h) measured at the canopy top is much greater over the closed canopy than the open canopy, contrary to earlier observations over a deciduous forest. But $C_{D*}^h = C_D^h/VAI$ (VAI is vegetation area index) is about the same over the closed and open canopies (~ 0.03 in near-neutral stability). The drag coefficient (C_d) for the parameterization of drag force in mean momentum budget equations in closure models increases with decreasing wind speed and varies with height. The drag coefficient (C_d^{LES}) for the parameterization of drag force in prognostic momentum equations in large-eddy simulations of airflow in plant canopies is smaller than

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C_d, and the ratio C_d^{LES}/C_d is greater in the open canopy than closed canopy and in stable than near-neutral and unstable conditions due to smaller relative turbulence intensities. All drag coefficients decrease and the displacement height increases with increasing stability, which indicates that these estimated aerodynamic parameters are not entirely the properties of vegetation elements, but are influenced by vertical turbulent mixing of momentum. Both eddy-diffusivity and mixing-lengths for momentum transfer decrease with increasing stability. An evidence of non-local transport is shown by peak values in estimated eddy-diffusivity and mixing-lengths below the crowns of mature aspen trees in the closed canopy. Otherwise, the eddy-diffusivity decreases with increasing depth into the forest, while the mixing-lengths above the level of the peaks are greater in the open canopy and the opposite is true below the level of the peaks.

1.   Introduction

Quantifications of both mean flow and turbulence statistics are needed to study scalar dispersion and diffusion in and above plant canopies. A practical example is the estimates of scalar concentration and flux footprints using analytical solutions of diffusion equations or Lagrangian stochastic models (Schmid, 2002). These flow statistics may be produced by ensemble average turbulence models at various orders of closure (Wilson and Shaw, 1977; Li et al., 1985; Meyers and Paw U, 1986, 1987; Wilson, 1988; Massman and Weil, 1999; Katul et al., 2004). However, most of the closure models have been applied to neutral stratification, and their predictions have not always been satisfactory when compared against field measurements (Meyers and Paw U, 1986; Wilson, 1988; Katul and Albertson, 1998). This could be in part due to uncertainties in the parameterizations used in current second- and third-order closure models. An example is the velocity–pressure-gradient covariance terms which are shown to be important (Su et al., 1998a). Other sources of uncertainties may lie in the value of the drag coefficient used in these closure models, and the mixing-length and zero-plane displacement height used in first- (Li et al., 1985) and 1.5-order closure models (Katul et al., 2004). Most of the closure models cited above have been used in a 1D (vertical) framework, even though the second-order closure model of Ayotte et al. (1999) can be applied in 2D (vertical and transverse). However, previous observations and modeling work have shown that significant horizontal mean wind directional shear can occur inside forest canopies (Smith et al., 1972; Pinker and Holland, 1988; Lee et al., 1994; Pyles et al., 2004). In such situations, an appropriate modeling framework for airflow inside forests should be at least 2D for a given reference of the streamwise direction such as the mean wind direction at the canopy top (Lee et al., 1994).

Field experiments that aim to characterize both the mean and turbulent wind fields inside forest canopies are still valuable today. In addition to providing direct measurements of the flow statistics, these measurements can be used to evaluate the drag coefficients, the displacement height, the mixing-length and eddy-diffusivity that are needed in various models of airflow inside forests. Previous observations in various forests have shown that both canopy morphology and thermal stability have significant impacts on the character-istics of turbulence statistics (Shaw et al., 1988; Leclerc et al.,

1990, 1991; Amiro, 1990a,b; Lee and Black, 1993; Katul and Albertson, 1998). However, the number of these observations is quite small compared to the variety of canopy morphology of real world forests. For example, in the mixed hardwood forest at the University of Michigan Biological Station (UMBS), there are two peaks in the vertical profile of vegetation area density (VAD) in the fully leafed canopy during the growing season, corresponding to the crowns of mature aspen trees in the upper canopy and young white pines in the understory, respectively. A first effort to measure turbulence statistics inside this forest was made in the summer of 2000 (Villani et al., 2003) but only 1D (vertical) sonic anemometers were available for measurements inside the canopy. All of these previous field observations were conducted in relatively short time periods (a few weeks to a couple of months).

The present study is based on a field experiment conducted from mid-June of 2004 to mid-August of 2005 inside the UMBS forest. Five 3D sonic anemometer-thermometers were installed at different heights above ground $z = 0.07–1h$ (h is the mean canopy height) on a small canopy tower. We obtained a much more extensive amount of data than in previous observations in forest canopies, which is useful to examine the relative significance of the influences of seasonal changes in canopy morphology and thermal stability on both mean flow and turbulence statistics in the UMBS forest.

2.   Methods

2.1.   Site and instruments

Data presented here were collected in a mixed hardwood forest at the University of Michigan Biological Station (UMBS) in northern lower Michigan ($45°35'$N, $84°42'$W). A detailed description of this AmeriFlux site (topography, vegetation composition, vegetation area index or VAI, soil type, mean canopy height, flux tower structure, instrumentation, etc.) is given in Schmid et al. (2003). The most significant topographic feature is the crest of an interlobate moraine approximately 1 km to the southwest of the flux tower with a relative elevation of about 30 m. The annual courses of VAI in 2004 and 2005 (Fig. 1a) were measured along seven different paths through a 60 m main plot surrounding the two towers at this site. Each measurement is the ensemble average of 120–130
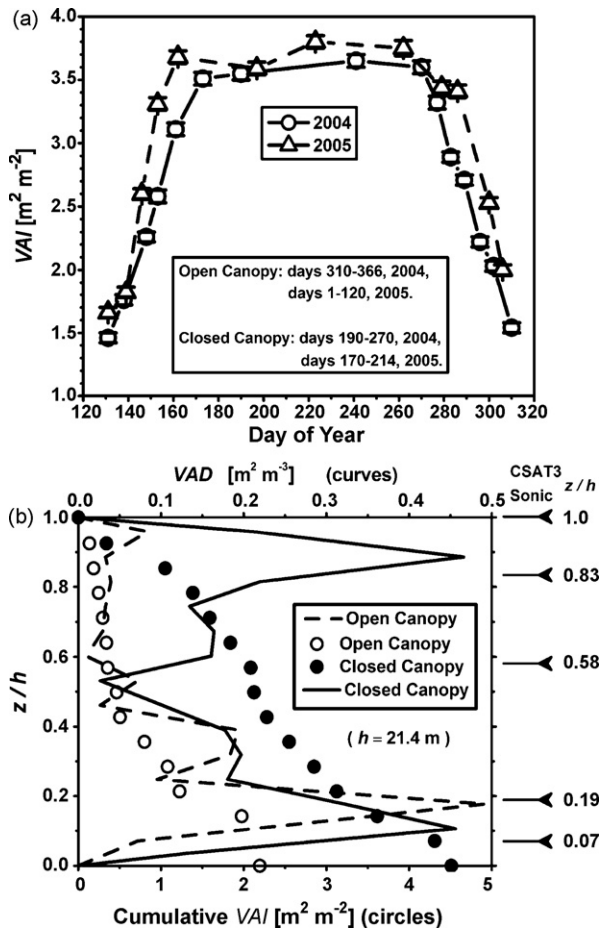
Fig. 1 – (a) Seasonal courses of vegetation area index (VAI).
(b) Vertical profiles of vegetation area density (VAD) and
cumulative VAI which is the vertical integration of VAD
from top down.

individual samples along a total path distance of 320 m.
Vertical profiles of VAD (total area of one side of all vegetation
material per unit volume) and cumulative VAI (vertical
integration of VAD from the canopy top towards the ground)
are measured on a 24.4 m tall tower which has a small
trianguler cross section (0.36 m face) located about 20 m
northwest of the 46 m tall main AmeriFlux tower which has a
much greater cross section. Each measurement of VAD at a
given height above ground (z) is the ensemble average of
samples taken over 12 azimuths. The VAI and VAD are
measured using LAI-2000 plant canopy analyzer (Li-cor Inc.). A
more detailed discussion on the measurement procedure is
given in Schmid et al. (2003). It is noted that VAI measured at
the smaller tower (Fig. 1b) is greater for both fully leafed
canopy (4.5) and after leaf fall of deciduous species (2.2) than
that averaged over the 60 m plot (3.6 and 1.6 in Fig. 1a). There
are two peaks in the VAD profile in the fully leafed canopy, the
top peak mainly reflects the crowns of mature aspen trees and
disappears after leaf fall. The lower peak is mainly due to
young white pines in the understory.

Five Campbell Scientific Inc. CSAT3 3D sonic anemometer-
thermometers were installed on the 24.4 m tower at heights
that took into account of the VAD profile characteristics

(Fig. 1b). The top level CSAT3 was located just above the
canopy at $z = 21.4$ m. For simplicity and convenience, but also
due to the lack of a precise definition of the canopy top, we
designate this height as $h = 21.4$ m. A second CSAT3 was
installed at $z/h = 0.83$, which is just below the level of the top
peak VAD. Similarly, a pair of CSAT3s were installed at $z/h = 0.19$ and 0.07, which are above and below the lower level
peak VAD. The fifth CSAT3 was at $z/h = 0.58$. Two main
considerations in the horizontal orientations of the CSAT3s
are to point them in the prevailing wind directions (deter-
mined from earlier observations on the main AmeriFlux tower
above the canopy) to minimize flow distortion by the tower,
and to keep them away from nearby vegetation elements as
far as possible to minimize flow distortion by individual trees.
Four CSAT3s pointed to 291°, which is close to the direction the
two CSAT3s on the main AmeriFlux tower point to (300°). The
only exception is the CSAT3 at $z/h = 0.83$, which pointed to 266°
before day 280 of 2004 and to 258° afterwards. The adjustments
for this level were necessary to avoid being hit by branches in
the crown of nearby aspen trees in windy conditions. The
azimuth angles are in meteorological convention. All five sonic
anemometer-thermometers are sampled and saved at 10 Hz.

As noted in Fig. 1a, we use data collected in days 190–270 of
2004 and days 170–214 of 2005 to represent the fully leafed
forest or ''Closed Canopy'', and days 310–366 of 2004 and days
1–120 of 2005 to represent the ''Open Canopy'' in the period
after complete leaf fall of deciduous species and before bud
break.

2.2. Data analysis

Basic quality analyses of the raw 10 Hz data include the
detection of ''hard'' and ''soft'' flags (Vickers and Mahrt,
1997; Schmid et al., 2003). A simple block-average with an
average time of 1 h was used for the Reynolds decomposition
to calculate mean (denoted by an overbar) and turbulent
(denoted by a prime) quantities. Hourly records of 10 Hz data
with total number of flags more than 600 (1 min) are
excluded. Only hourly runs that all five level 10 Hz raw data
pass this screening are used for the results presented here.
This is mainly because many of the discussions concern the
vertical profiles of mean flow and turbulence statistics,
which are often normalized by quantities measured at the
canopy top.

Similar to previous analyses of 3D sonic anemometer-
thermometer measurements of turbulence inside forest
canopies (Baldocchi and Hutchison, 1987; Shaw et al., 1988;
Amiro, 1990a,b), a coordinate rotation was first applied in the
horizontal plane to force the lateral or spanwise mean velocity
($\bar{v}$) to zero at each height. None of the cited earlier studies
applied a second rotation in the x–z plane to force the hourly
mean vertical velocity ($\bar{w}$) to zero inside the canopy. The
rationale is that individual vegetation elements can distort the
flow and cause locally non-zero mean vertical velocities inside
the canopy. Other physical processes that may produce non-
zero vertical velocities for individual hourly runs both within
and above the canopy are discussed in Lee (1998).

Several practical methods have been proposed to correct
the sonic anemometer's tilt relative to local long-term
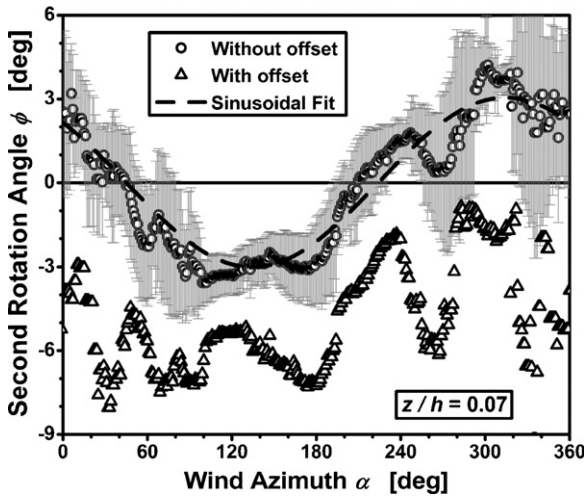averaged mean streamline surface (Finnigan et al., 2003;

Fig. 2 – The effect of sonic anemometer-thermometer's offset on the second rotation angle ϕ.

simple terrain where underlying surface has a uniform slope, and in the absence of flow distortions and sonic anemometer-thermometer's offsets, the ensemble (moving-bin) averaged ϕ would be a sinusoidal function of α. The amplitude of this sinusoidal function would be the tilt angle between the sonic anemometer-thermometer's x–y plane and the local streamline surface (Su et al., 2008).

Before installing the CSAT3s on the tower, we measured the offsets of all three velocity components for each CSAT3 in a closed zero wind chamber in the lab, following the procedure recommended in the CSAT3 manual. The offsets slightly vary among the CSAT3s but in similar magnitude of $\pm(1–3) \times 10^{-2}$ m s^{-1}. The effect of the offsets on the ensemble averaged ϕ is expected to be relatively large at the lowest two measurement levels due to low wind speed. For example, at $z/h = 0.07$, the offsets introduce a bias in the moving-bin averaged ϕ of about $-4.5°$ averaged over all wind directions (Fig. 2). In addition, the moving-bin averaged ϕ fits a sinusoidal function of α quite well when the offsets are removed. This may be expected since the elevations change little (about 234 m above mean sea level) within 500 m radius from the flux tower in all directions (Schmid et al., 2003). A second rotation is performed in the x–z plane using the moving-bin averaged ϕ with the effects of the offsets removed. This procedure is applied to each of the five CSAT3s.

The main objectives of this paper is to examine the relative significance of influences of canopy morphology and stability

Finnigan, 2004; Lee et al., 2004). One of them (Lee, 1998; Baldocchi et al., 2000; Finnigan et al., 2003; Su et al., 2004) uses the ensemble average of the second rotation angle (ϕ) in the x–z plane which varies with the wind azimuth (α). Another is the planar fit method (Paw U et al., 2000; Wilczak et al., 2001). Over
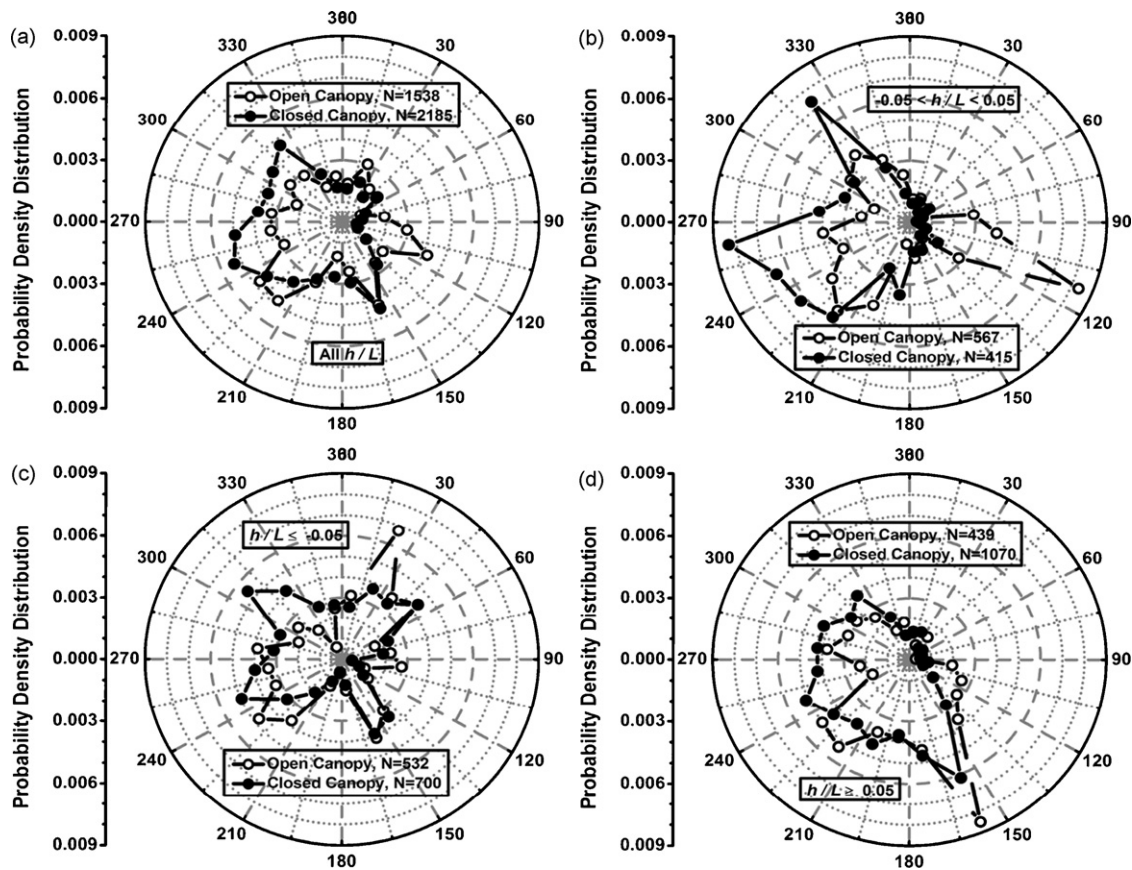

Fig. 3 – Windroses at the canopy top for different groups of canopy morphology and stability, in which N is the total number of hourly runs for each group. The probability density is calculated as the number of hourly runs in each 15° bin of azimuths divided by N and the bin size.
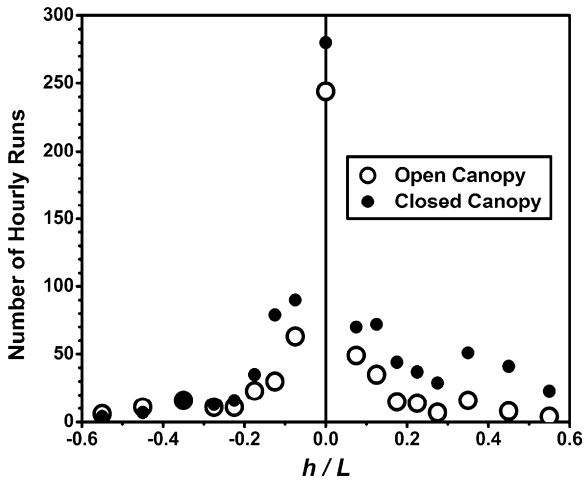
Fig. 4 – The numbers of hourly runs for 17 stability classes when incoming wind directions α are between 210° and 330°.

on both the mean flow and turbulence statistics in the UMBS forest. Following Shaw et al. (1988), we use a single stability parameter h/L, where L is the Monin–Obukhov length calculated using measurements at the canopy top. Results presented below are based on data collected during periods when the incoming wind direction at the canopy top is in the azimuth range of $210° < \alpha < 330°$ which are the prevailing wind directions (Fig. 3a). There are ample data in this azimuth range in near-neutral (Fig. 3b), unstable (Fig. 3c) and stable (Fig. 3d) conditions for both the open and closed canopies. We also found that variations in ensemble averaged mean and turbulence statistics with wind directions in near-neutral conditions are small in this azimuth range, which may be expected since the upwind fetch is over 1 km with little change in elevations in these directions. Therefore, we may assume horizontal homogeneity in the discussions that follow. Furthermore, there are very few hourly runs for closed canopy when $h/L < -0.6$ and for open canopy when $h/L > 0.6$ (Fig. 4). Thus, we only present mean and turbulence statistics in the stability range of $-0.6 \leq h/L \leq 0.6$.
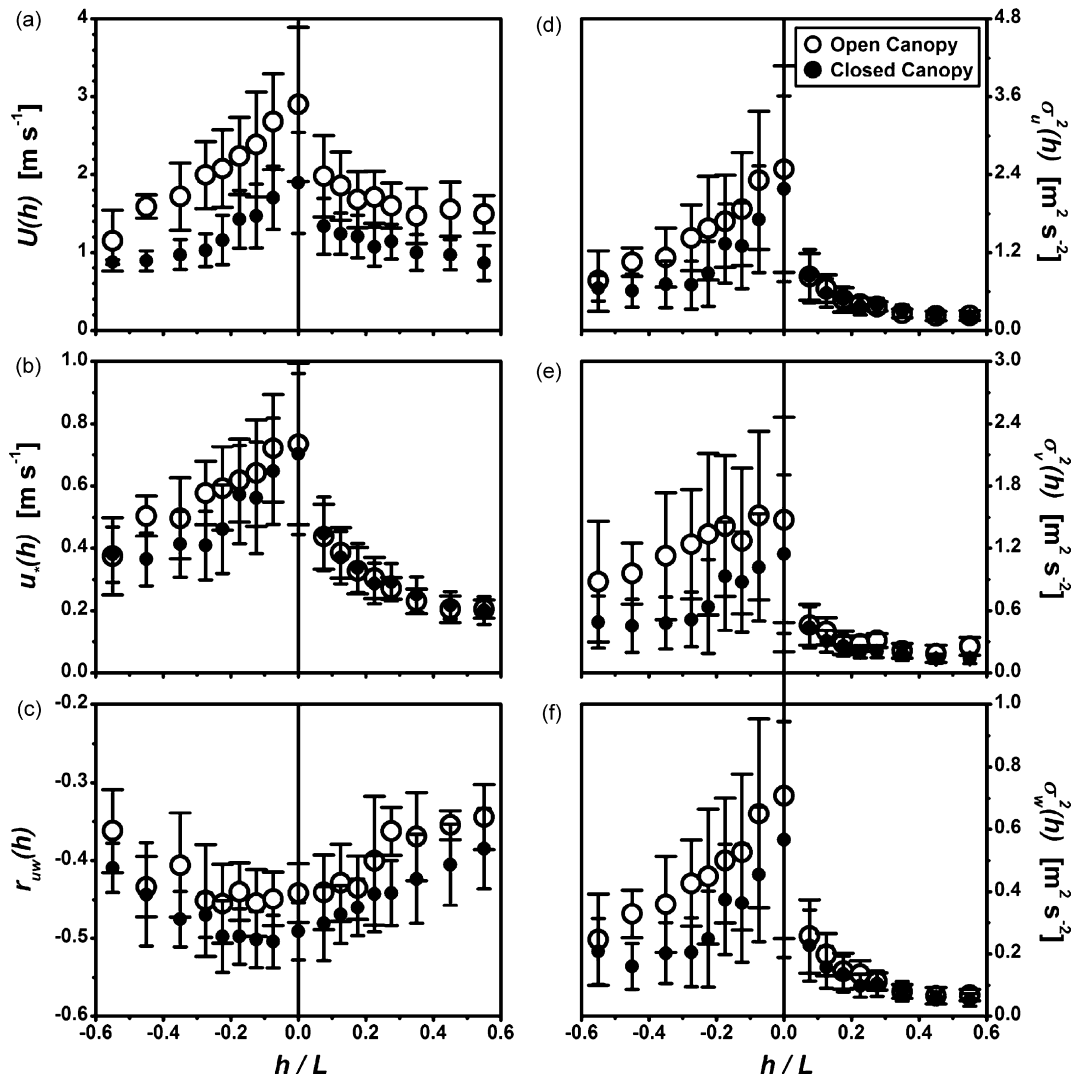

Fig. 5 – Comparison of ensemble averaged first- and second-order velocity statistics at the top of the UMBS forest between the open and closed canopies and their variations with stability.

3. Results and discussions

First, we compare typical first- and second-order single-point velocity statistics at the top of UMBS forest between the open and closed canopies (Fig. 5). These include mean wind speed $U(z) = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2}$, friction velocity $u_*(z) = \left[\overline{u'w'}^2 + \overline{v'w'}^2 \right]^{1/4}$, correlation coefficient $r_{uw}(z) = \overline{u'w'}/\sigma_u \sigma_w$, velocity variances $\sigma_u^2(z) = \overline{u'^2}$, $\sigma_v^2(z) = \overline{v'^2}$ and $\sigma_w^2(z) = \overline{w'^2}$, where u, v, w are velocities in the x-, y- and z-direction of the long-term averaged streamline coordinate.

Ensemble averaged $U(h)$ is greater over the open canopy than the closed canopy in all classes of h/L. In comparison, ensemble averaged $u_*(h)$, $\sigma_u^2(h)$, $\sigma_v^2(h)$ and $\sigma_w^2(h)$ are greater over the open canopy when $-0.6 \leq h/L \leq 0$ but about the same between the open and closed canopies when $h/L > 0$. The ratio between $u_*(h)$ and $U(h)$ is discussed in terms of the bulk drag coefficient later in Section 3.6. In contrast, ensemble averaged $r_{uw}(h)$ is more negative (stronger correlation) over the closed canopy than the open canopy in all classes of h/L with an average difference of about -0.05. In addition, $r_{uw}(h)$ in near-neutral conditions over both the open (-0.45) and closed (-0.5) canopies is more negative than those (-0.3 to -0.35) observed in the inertial surface layer over smooth surfaces (Kaimal and Finnigan, 1994). Shaw et al. (1988) observed similar values of $r_{uw}(h)$ in near-neutral conditions but $r_{uw}(h)$ is more negative (-0.5) over defoliated canopy (LAI = 0.3) than (-0.45) fully leafed canopy (LAI = 4.9). More negative r_{uw} in the roughness sublayer above forests than in the inertial sublayer over smooth surfaces has been interpreted as turbulence in the former is more efficient in transporting momentum (Raupach et al., 1996; Finnigan, 2000).

As expected, ensemble averaged $U(h)$, $u_*(h)$, $\sigma_u^2(h)$, $\sigma_v^2(h)$ and $\sigma_w^2(h)$ are the greatest in near-neutral conditions and decrease with increasing instability or stability. The decreases are the most rapid from $h/L = 0$ to 0.2. On the other hand, ensemble averaged $r_{uw}(h)$ is the most negative and relatively constant from near-neutral stability to $h/L \approx -0.2$, and the correlation decreases (becomes less negative) with increasing instability or stability. Thus, to simplify some of the discussions that follow, ensemble averaged vertical profiles of mean flow and turbulence statistics in $-0.6 \leq h/L < -0.2$, $-0.05 < h/L < 0.05$
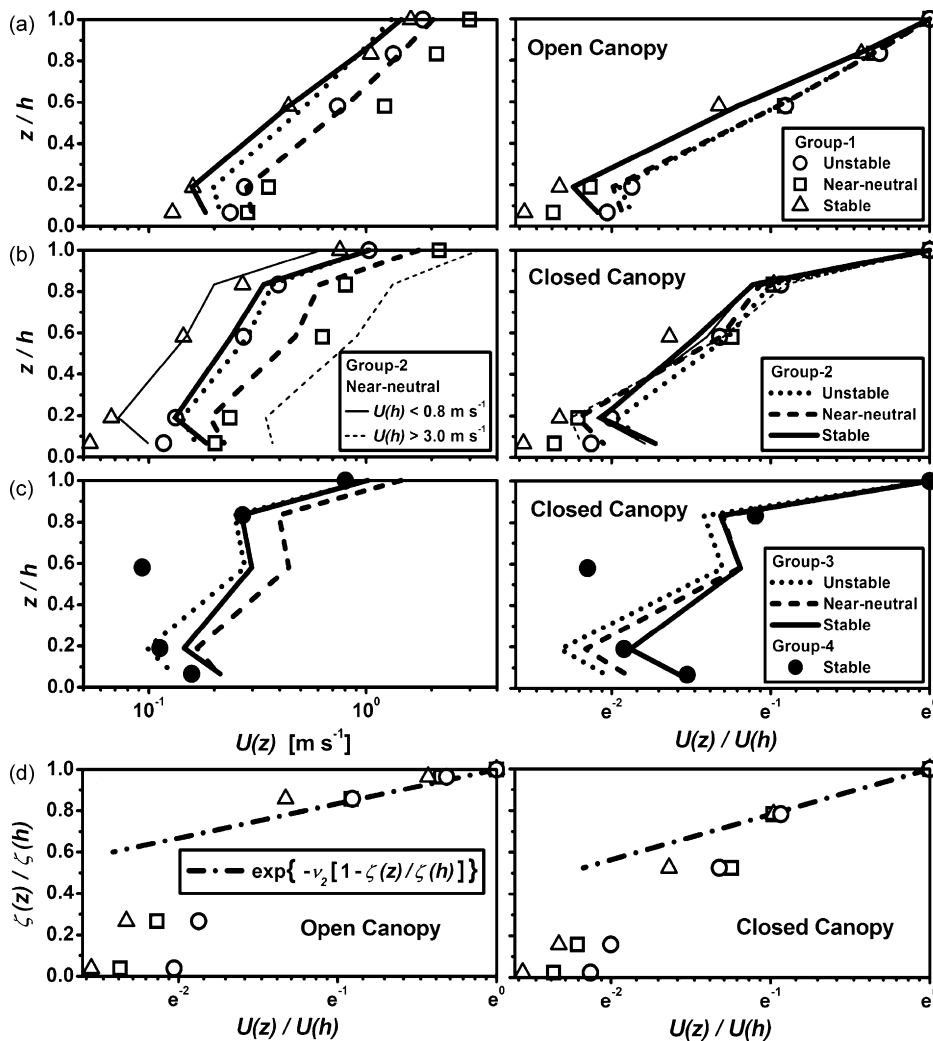

Fig. 6 – Ensemble averaged $U(z)$ and $U(z)/U(h)$ as functions of normalized height z/h: (a)–(c); or as functions of normalized cumulative vegetation drag area index $\zeta(z)/\zeta(h)$: (d). Note that $U(z)$ is plotted in logarithmic scale for clarity, and $U(z)/U(h)$ is plotted in natural logarithmic scale for discussions on the exponential formulas.

and $0.2 < h/L \leq 0.6$ are used to represent the three stability categories of unstable, near-neutral and stable, respectively.

3.1. Vertical profiles of mean wind speed

Shaw (1977) noted that wind profiles measured in forest and crop canopies "normally" contain a secondary maximum or a region of very small shear beneath the level of greatest foliage density. Our observations show that both the frequency of occurrence and the strength of secondary wind speed maxima vary with canopy morphology and thermal stability. Here we separate vertical profiles of mean wind speed $U(z)$ in four groups with different characteristics of $\partial U(z)/\partial z$ (Fig. 6). The first two groups are observed in both the open (Fig. 6a) and closed (Fig. 6b) canopies in all three stability categories. There is no secondary wind speed maximum in Group-1, and a secondary wind speed maximum is observed at the lowest measurement level ($z/h = 0.07$) with $\partial U(z)/\partial z < 0$ between $z/h = 0.19$ and 0.07 in Group-2. Two additional groups are observed only in the closed canopy (Fig. 6c). Group-3 exhibits two secondary wind speed maxima at $z/h = 0.07$ and 0.58 in all three stability categories with $\partial U(z)/\partial z < 0$ in two layers ($z/h = 0.19$–0.07 and 0.81–0.58) and $\partial U(z)/\partial z > 0$ between $z/h = 0.58$ and 0.19. Group-4 is observed only in stable conditions with a secondary wind maximum also at $z/h = 0.07$ but $\partial U(z)/\partial z < 0$ from $z/h = 0.58$ to 0.07.

Group-2 is observed a lot more frequently not only in the closed canopy than in the open canopy for the same stability category (near-neutral: 52% vs. 9%; unstable: 46% vs. 13%; stable: 84% vs. 20%), but also in stable than in near-neutral and unstable conditions for the same canopy morphology. Group-3 (near-neutral: 7%; unstable: 15%; stable: 9%) and Group-4 (stable: 4%) are observed much less frequently than Group-2 for the same stability. Here the percentages are relative to the total number of hourly runs in the same stability category for the same canopy morphology (Fig. 4). If the offsets of the CSAT3s are not removed, all four groups are still observed although their percentages change somewhat. However, the relative significance of these percentages do not change qualitatively. For example, Group-2 remains to be the most frequent (76%) in the closed canopy under stable conditions. By definition, the magnitude of $U(z)$ and thus the observed secondary wind speed maxima do not change whether or not the second rotation in the x–z plane is performed.

In addition, the secondary wind speed maximum at $z/h = 0.07$ is more pronounced in the closed canopy than in the open canopy for the same stability (Fig. 6a and b), and is the most pronounced in stable conditions for the same canopy morphology (Fig. 6a–c). It is also much more pronounced when $U(h) < 0.8 \text{ m s}^{-1}$ than when $U(h) > 3.0 \text{ m s}^{-1}$ in the closed canopy under near-neutral conditions (Fig. 6b). In comparison, the secondary wind speed maximum at $z/h = 0.58$ is less pronounced than that at $z/h = 0.07$ in the same stability category (Fig. 6c).

For airflow in horizontally homogeneous plant canopies on flat ground, a number of turbulent closure models (Cionco, 1965; Shaw, 1977; Wilson and Shaw, 1977; Li et al., 1985; Meyers and Paw U, 1986; Wilson, 1988; Massman, 1997; Katul et al., 2004) include vertical divergence of Reynolds stress as the only source of mean wind speed (downward penetration or

transport of momentum), while others (Smith et al., 1972; Kondo and Akashi, 1976; Yamada, 1982; Lee et al., 1994; Pyles et al., 2004) also include a mean horizontal pressure-gradient force. The mean canopy drag, $C_d(z) \cdot VAD(z) \cdot U^2(z)$, is usually the only sink included in mean momentum budget in these models, where $C_d(z)$ is an effective mean drag coefficient (discussed later in Section 3.6). In principle, the Coriolis force only changes the mean wind direction but not the mean wind speed, and is usually an order of magnitude smaller than the other three forces inside plant canopies (Lee et al., 1994) and neglected in most canopy turbulence models.

The second-order closure model of Wilson and Shaw (1977) was shown to be able to produce a weak (in a corn crop and a coniferous stand) to moderate (in a deciduous forest) secondary wind speed maximum below the level of maximum vegetation density without a mean horizontal pressure-gradient force (Lee et al., 1994). An explanation suggested by Shaw (1977) is that the vertical gradient of mean wind speed can reverse in sign if the vertical divergence of turbulent transport of Reynolds stress is of opposite sign and exceeds in magnitude the pressure–velocity-gradient covariance in the budget of Reynolds stress. Kondo and Akashi (1976) showed that modeled secondary wind maximum became more pronounced with increasing vegetation density. Lee et al. (1994) demonstrated that below the level of maximum VAD in the two forests where the vertical divergence of Reynolds stress is very small, modeled $U(z)/U(h)$ increases and secondary wind speed maximum becomes more pronouced with increasing mean horizontal pressure-gradient. In contrast, the magnitude of mean horizontal pressure-gradient has little influence on modeled $U(z)/U(h)$ in the upper part of the two forests above the level of maximum VAD where the vertical divergence of Reynolds stress is much more significant.

Our observations in the UMBS forest agree with these modeling studies and previously observed mean wind speed profiles in various forests (Fons, 1940; Reifsnyder, 1955; Allen, 1968; Landsberg and James, 1971; Oliver, 1971; Baldocchi and Meyers, 1988; Lee and Black, 1993; Pyles et al., 2004) in that secondary wind speed maxima are observed below the level(s) of peak VAD and in periods when the vertical divergence of Reynolds stress is small (discussed later in Section 3.3), and that the secondary wind maximum at $z/h = 0.07$ is more pronounced in the closed (denser) canopy than in the open canopy for the same stability. However, none of the earlier observations show two secondary wind speed maxima as we observed in the closed canopy at UMBS (Fig. 6c), which apparently correspond to the two peaks in the vertical profile of VAD (Fig. 1b).

In addition, previous measurements in various forests have reported a different relation between stability and the strength of secondary wind maximum from our observations in the UMBS forest. Reifsnyder (1955) observed that the secondary maximum is not as sharply defined under inversion conditions as under lapse conditions in a small isolated forest stand. Oliver (1971) reported that the secondary maximum in a pine forest increases with increased instability indicated by a Richardson number measured above the forest. Pyles et al. (2004) showed that the secondary wind speed maximum observed at $z/h = 0.15$ below the layer ($z/h = 0.2$–0.3) of maximum vegetation density in an old-growth temperate

rainforest are the most pronounced in daytime unstable conditions when net radiation (R_n) measured above the forest is greater than 100 W m^{-2}, weaker in near-neutral conditions ($-20 < R_n \le 100$ W m^{-2}), and disappear in nocturnal stable conditions ($R_n < -20$ W m^{-2}). However, their modeled mean wind profiles show that the secondary wind maximum is the most pronounced in stable, weaker in near-neutral and disappears in unstable conditions, which agree with our observations in the UMBS forest. Factors that contribute to the differences in stability effect on the strength of secondary wind speed maximum may include differences in canopy morphology and magnitudes of mean horizontal pressure-gradient force, even though the latter was not measured in all field experiments cited here. Other factors such as those discussed in Shaw (1977) may also be important in a particular forest. For example, horizontal advection, blow-through or edge effect due to inadequate fetch may be important in the small isolated forest (Reifsnyder, 1955). On the other hand, topographic effects could be important at the study site of Pyles et al. (2004).

Exponential formulas such as $U(z)/U(h) \exp[-\nu_1(1 - z/h)]$ (Inoue, 1963) and $U(z) = U(h) \exp\{-\nu_2[1 - \zeta(z)/\zeta(h)]\}$ (Albini, 1981) where $\zeta(z) = \int_0^z C_d(z') \cdot \text{VAD}(z') \, dz'$ is a cumulative vegetation drag area index (Massman, 1997), are incapable of modeling a secondary wind speed maximum. The extinction coefficient $\nu_2 = 0.5\zeta(h)/C_D^h$ may vary with canopy morphology but is independent of height, where C_D^h is the bulk canopy drag coefficient measured at the canopy top (discussed later in Section 3.6). The extinction coefficient ν_1 may be independent of height if $C_d(z) \cdot \text{VAD}(z)$ is constant with height (Cionco, 1965; Massman, 1997). However, even in the absence of a secondary wind speed maximum (Group-1), measured $\ln[U(z)/U(h)]$ inside the UMBS forest is not a linear function of either z/h (Fig. 6a and b) or $\zeta(z)/\zeta(h)$ (Fig. 6d) in both the open and closed canopies, which indicates that neither ν_1 nor ν_2 is constant with height. In addition, the attenuation of mean wind speed in the upper part of UMBS forest is greater in stable than near-neutral and unstable conditions, which indicates that both ν_1 and ν_2 also vary with stability.

3.2. Vertical profiles of horizontal mean wind directional shear

Here the horizontal mean wind direction difference is calculated as the incoming wind direction at a given depth in the forest minus that at the canopy top. Ensemble averages of observed horizontal mean wind direction differences are all negative (Fig. 7), which indicates that horizontal mean winds inside the UMBS forest generally flow to the left (counter-clockwise) of the mean wind at the canopy top. This is in qualitative agreement with previously observed and modeled horizontal mean wind directional shear in various forests (Smith et al., 1972; Pinker and Holland, 1988; Lee et al., 1994; Pyles et al., 2004).

Since the greatest differences in VAD between the open and closed canopies are in the top layer ($z/h = 1$–0.83) (Fig. 1b), we use ensemble averaged wind direction differences measured at $z/h = 0.83$ to discuss the effects of vegetation density, thermal stability and mean wind speed. First, the horizontal mean wind directional shear in the top layer is greater in the
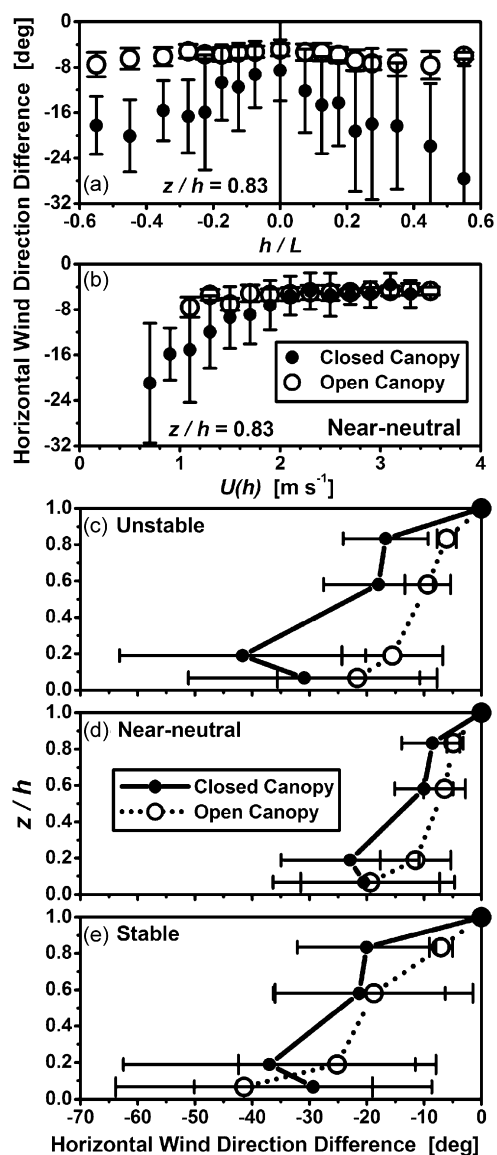

Fig. 7 – Influences of canopy morphology, thermal stability and wind speed on horizontal mean wind directional shear inside the UMBS forest.

closed canopy than in the open canopy in all classes of h/L (Fig. 7a). Second, this shear is the smallest in near-neutral stability and increases with increasing instability and stability in both the open and closed canopies. Third, the effect of stability is much greater in the closed canopy than in the open canopy, and the difference in the shear between the closed and open canopies is also the smallest in near-neutral conditions and increases with increasing instability and stability. Fourth, in near-neutral conditions (Fig. 7b), the shear does not vary much with $U(h)$ and there is little difference in the shear between the closed and open canopies when $U(h) > 2$ m s^{-1}. However, the shear increases with decreasing $U(h)$ when $U(h) < 2$ m s^{-1}, and the decrease is much more rapid in the closed canopy than in the open canopy. Thus, the difference in the shear between the closed and open canopies increases with decreasing $U(h)$.

Except from $z/h = 0.19$ to 0.07 in the closed canopy, the ensemble averaged horizontal mean wind direction differences increase with increasing depth into the forest in both the open and closed canopies. But the rate of increase or the horizontal mean wind directional shear between two adjacent measurement levels varies with canopy morphology and thermal stability. In unstable (Fig. 7c) and near-neutral (Fig. 7d) conditions, the shear in the layer $z/h = 0.83–0.58$ is similar between closed and open canopies but is smaller than the shear in the top layer. In stable conditions (Fig. 7e), the shear in $z/h = 0.83–0.58$ is much smaller in the closed canopy than in the open canopy. On the other hand, the shear in $z/h = 0.58–0.19$ is also greater in the closed canopy than in the open canopy in all three stability categories. Between the lowest two measurement levels ($z/h = 0.19–0.07$), the shear remains to be counter-clockwise in the open canopy and is the greatest in stable conditions, but becomes clockwise in the closed canopy and is greater in unstable and stable conditions than in near-neutral stability.

The observed effects of canopy morphology agree qualitatively with previous modeling studies. Kondo and Akashi (1976) and Lee et al. (1994) showed that modeled horizontal mean wind directional shear depends on the vertical distribution of vegetation density, and the modeled shear is not only the greatest in the canopy layer of maximum VAD in the upper forests, but also greater when VAD in this layer is larger (denser). Lee et al. (1994) also reported that the modeled shear is more sensitive to vegetation density than the magnitude of mean horizontal pressure-gradient force in neutral stability.

On the other hand, measurement and modeling of the stability effects on horizontal mean wind directional shear inside forests have been rare. Our observations indicate that the effect of thermal stability inside the UMBS forest can be as important as that of canopy morphology, but the influence of stability vary with height, vegetation density and its vertical distribution. Charateristics in the vertical profiles of the shear and their relation to stability observed in an old-growth temperate rainforest (Pyles et al., 2004) differ qualitatively with our observations in the UMBS forest, which could be in part due to differences in vegetation density and its vertical distribution between the two forests. In addition, Pyles et al. (2004) showed substantial (55°–80°) differences between observed and modeled wind directional shear in the lower part of the temperate rainforest in all three stability categories, which could be in part due to uncertainties in the parameterizations used in the closure model, particularly in stable conditions, and/or topographic effects at their study site.

In the UMBS forest, the maximum counter-clockwise rotation of horizontal mean wind (in reference to the mean wind at the canopy top) is about 41° at $z/h = 0.07$ in the open canopy in stable conditions and about 42° at $z/h = 0.19$ in the closed canopy in unstable conditions, which is similar to modeled maximum wind directional turn in a coniferous stand and a deciduous forest (Lee et al., 1994). This has been explained as a result of negligible vertical divergence of Raynolds stress in the lower forest so that the horizontal pressure-gradient force balances the drag force in the mean momentum budget equation (in analogy to antitriptic flow),

and the mean wind tends to align with the mean horizontal pressure-gradient force (Lee et al., 1994). The reversal (clockwise) of mean wind direction shear from $z/h = 0.19$ to 0.07 observed in the closed canopy at UMBS is also observed between the lowest two measurement levels from $z/h = 0.30$ to 0.15 in the temperate rainforest, but only in near-neutral and stable conditions. Pyles et al. (2004) discussed that this reversal could be a result of local mountain/valley breezes in the understory of the temperate rainforest, but their higher-order closure model failed to reproduce this clockwise rotation. The same mechanism is absent at the UMBS site since the elevation is quite uniform. On the other hand, accurate measurements of horizontal mean wind directional shear could be difficult in very low wind speed conditions, which are typical at the lowest two measurement levels in the closed canopy as indicated by very large standard deviations (Fig. 7).

3.3. Vertical profiles of Reynolds stress and correlation coefficient

The vertical profile of Reynolds stress is a more direct measure (than mean wind speed profile) of downward momentum penetration into plant canopies. The effects of increased vegetation density and stability on vertical profiles of normalized Reynolds stress observed in the UMBS forest (Fig. 8a) are in general agreement with the observations of Shaw et al. (1988). First, momentum penetrates deeper into the open canopy than the closed (denser) canopy as illustrated by greater $u_*^2(z)/u_*^2(h)$ at the same depth in the open canopy under near-neutral and unstable conditions. This is a result of much greater VAD and thus greater percentage of momentum absorption by the top layer ($z/h = 1–0.83$) in the closed canopy than in the open canopy (near-neutral: 69.1% vs. 29.5%; unstable: 68.3% vs. 27.1%; stable: 87.2% vs. 33.8%). Consequently, in the lower three layers where VAD in the closed canopy is no smaller than in the open canopy, relatively smaller percentages of momentum are absorbed in the closed canopy: $z/h = 0.83–0.58$ (near-neutral: 20.7% vs. 36.5%; unstable: 22.6% vs. 35.6%; stable: 9.0% vs. 43.5%), $z/h = 0.58–0.19$ (near-neutral: 8.4% vs. 30.6%; unstable: 6.5% vs. 32.0%; stable: 2.4% vs. 21.3%), $z/h = 0.19–0.07$ (near-neutral: 1.1% vs. 2.6%; unstable: 1.2% vs. 3.8%; stable: 0.5% vs. 0.3%). The penetration of momentum is also reduced in stable conditions as $u_*^2(z)/u_*^2(h)$ at the same depth of the forest is smaller in stable than near-neutral conditions, except near the forest floor ($z/h = 0.07$) where $u_*^2(z)/u_*^2(h)$ is less than 0.02 in all stability categories. The reduction of momentum penetration from near-neutral to stable conditions is also shown as the percentages of momentum absorbed by the top layer in the closed canopy and by the top two layers in the open canopy increase, while the percentages by the lower three layers in the closed canopy and by the lower two layers of the open canopy decrease. In addition, the effect of increased stability in the top two layers is greater in the closed canopy than in the open canopy, whereas the opposite is true in the lower two layers. Profiles of normalized Reynolds stress in unstable conditions are not shown in Shaw et al. (1988). At UMBS, differences in ensemble averaged vertical profiles of normalized Reynolds stress between near-neutral and unstable conditions are generally small as differences in $u_*^2(z)/u_*^2(h)$
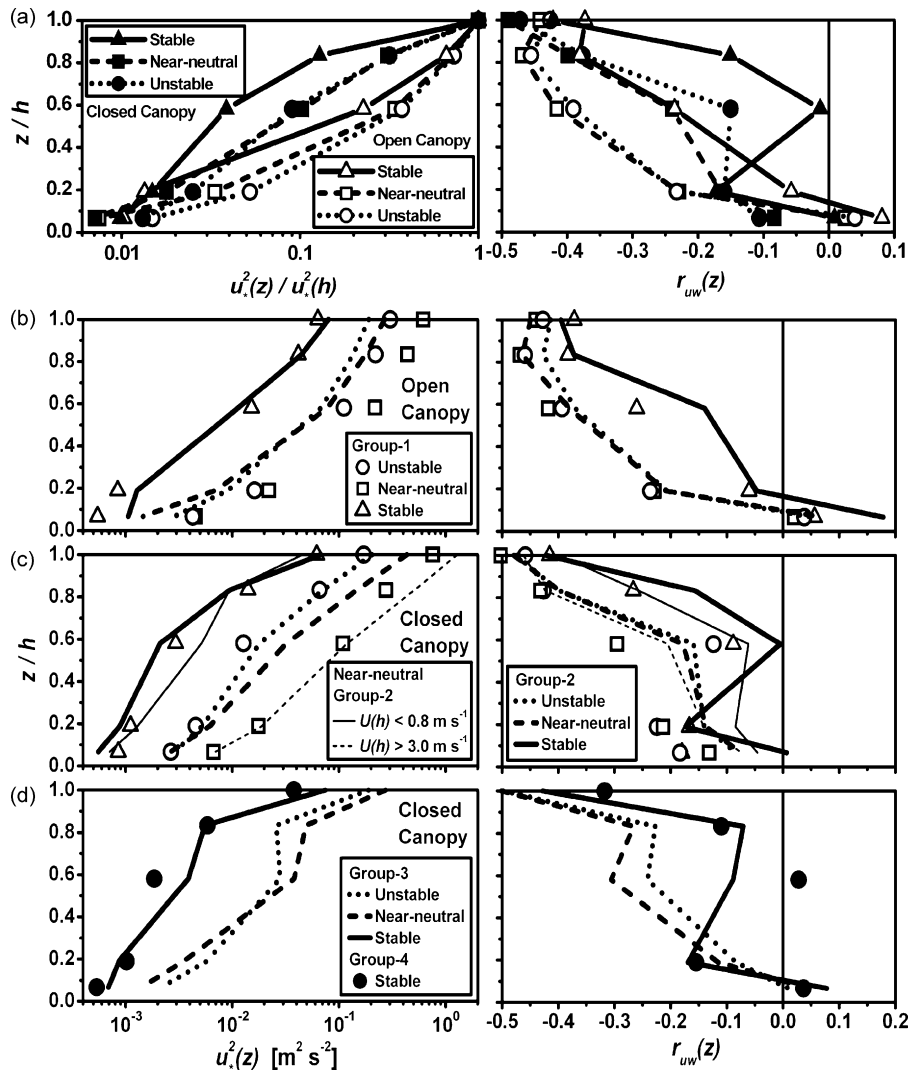
Fig. 8 – *Left panels*: ensemble averaged (a) normalized Reynolds stress $u_*^2(z)/u_*^2(h)$; (b)–(d) Reynolds stress $u_*^2(z)$. *Right panels*: ensemble averaged correlation coefficient $r_{uw}(z)$. The lines and symbols in (b)–(d) correspond to the four groups of mean wind speed profiles in panels (a)–(c) of **Fig. 6**.

at the same depth of the forest are less than 0.03 in both the open and closed canopies.

The vertical profile of r_{uw} is a measure of the efficiency of turbulence inside forests in transporting momentum and the attenuation rate of the correlation with increasing depth into the forest is another measure of the depth of downward momentum penetration. Shaw et al. (1988) observed that the strongest correlation is at $z/h = 0.87$ for LAI = 0.3–4.9 in near-neutral stability. This is similar to observed vertical profiles of r_{uw} in the open canopy at UMBS (most negative at $z/h = 0.83$) in all three stability categories (Fig. 8a). In contrast, the strongest correlation in the closed canopy at UMBS is at the canopy top. Our observations show $r_{uw}(h)$ is more negative over the closed (denser) canopy, which is opposite to the observations of Shaw et al. (1988). However, both studies show that $r_{uw}(h)$ is less negative at the same depth inside the denser forest. In the upper part ($z/h = 1$–0.58) of UMBS forest, the correlation decreases more rapidly with increasing depth into the forest in the closed canopy than in the open canopy, and in stable

than in unstable and near-neutral conditions. At $z/h = 0.58$, $r_{uw}(z)$ is nearly diminished in the closed canopy in stable conditions. This indicates that little momentum from above is transferred below this depth where the Reynolds stress is less than 1×10^{-3} m^2 s^{-2} (Fig. 8c and d), even though $r_{uw}(z)$ at $z/h = 0.19$ is more negative than at $z/h = 0.58$.

Here we also average the vertical profiles of $u_*^2(z)$ and $r_{uw}(z)$ (Fig. 8b–d) corresponding to the four groups of mean wind speed profiles (Fig. 6a–c). We found that $\partial u_*^2(z)/\partial z$ below $z/h = 0.19$ (Group-2, Group-3 and Group-4) and between $z/h = 0.83$ and 0.58 (Group-4) are less than 5×10^{-4} m s^{-2} in stable conditions and no greater than 2.4×10^{-3} m s^{-2} in near-neutral and stable conditions, which are equivalent to a surface horizontal pressure-gradient of 0.6–3 hPa (100 km)$^{-1}$ (Lee et al., 1994). In addition, ensemble averaged $\partial u_*^2(z)/\partial z$ below $z/h = 0.19$ is 5×10^{-4} m s^{-2} when $U(h) < 0.8$ m s^{-1} and 4.9×10^{-3} m s^{-2} when $U(h) > 3.0$ m s^{-1} for Group-2 in near-neutral conditions in the closed canopy (Fig. 8c). These results indicate that the smaller is $\partial u_*^2(z)/\partial z$, the more pronounced is

the secondary wind speed maximum (Fig. 6). However, ensemble averaged $\partial u_*^2(z)/\partial z$ below $z/h = 0.19$ for Group-1 has similar magnitude as Group-2 in stable conditions in both the open and closed canopies, and in unstable conditions in the closed canopy. Thus, while the magnitude of horizontal mean pressure-gradient force may be the cause of the secondary wind speed maximum (Lee et al., 1994), the magnitude of $\partial u_*^2(z)/\partial z$ can influence the strength of the secondary wind speed maximum. In addition, $r_{uw}(z)$ is less negative (indicating turbulence is less efficient in transporting momentum into the forest) when secondary wind speed maximum is observed than when it is absent (right panels in Fig. 8b–d), especially in the upper part ($z/h = 1 - 0.58$) of the UMBS forest.

3.4. Vertical profiles of velocity variances and relative turbulence intensities

In near-neutral stability, ensemble averages of the normalized velocity variances at the canopy top (Fig. 9a) are $\sigma_u^2(h)/u_*^2(h) = 4.27$ and 4.02, $\sigma_v^2(h)/u_*^2(h) = 2.48$ and 2.10, $\sigma_w^2(h)/u_*^2(h) = 1.21$ and 1.03, over the open and closed canopies, respectively. These values agree with the observations of Shaw et al. (1988) in that they are smaller than those ($\sigma_u^2/u_*^2 = 5.76$, $\sigma_v^2/u_*^2 = 4.4$, $\sigma_w^2/u_*^2 = 1.6$) observed in the inertial surface layer over smooth surfaces (Garratt, 1992), which is also interpreted as turbulence in the roughness sublayer above plant canopies is more efficient in transporting momentum (Raupach et al., 1996; Finnigan, 2000). Shaw et al. (1988) did not report stability effect but showed that in near-neutral stability, $\sigma_u^2(h)/u_*^2(h)$ increases with increasing LAI and $\sigma_w^2(h)/u_*^2(h)$ is the same for LAI = 0.3–4.9. In contrast, we observed that these normalized velocity variances decrease with increasing VAI in near-neutral stability, and are greater in stable and unstable conditions than in near-neutral stability except that $\sigma_u^2(h)/u_*^2(h)$ is about the same in unstable and near-neutral conditions.

Ensemble averaged $\sigma_u^2(z)/u_*^2(h)$, $\sigma_v^2(z)/u_*^2(h)$ and $\sigma_w^2(z)/\sigma_w^2(h)$ at the same depth of the UMBS forest are greater in the open canopy than in the closed canopy as their attenuations with increasing depth into the forest are more rapid in the closed canopy than in the open canopy, especially in the top layer ($z/h = 1-0.83$) of the forest (Fig. 9a). The effect of increased VAD on $\sigma_u^2(z)/u_*^2(h)$ is much greater than that of stability, while the two effects on $\sigma_v^2(z)/u_*^2(h)$ and $\sigma_w^2(z)/u_*^2(h)$ are of similar magnitude. In addition, the attenuations of $\sigma_u^2(z)/u_*^2(h)$ and $\sigma_w^2(z)/u_*^2(h)$ are the most and least rapid, respectively. Consequently, differences among the three velocity variances decrease with increasing depth into the forest. For example, in the closed canopy, these differences become very small at $z/h = 0.83$ and the velocity variances are nearly isotropic in unstable and stable conditions. At the lowest two measurement levels, $\sigma_w^2(z)/u_*^2(h)$ continues to diminish as the forest floor is approached. This is not the case for $\sigma_u^2(z)/u_*^2(h)$ and $\sigma_v^2(z)/u_*^2(h)$, which either remain relatively constant or increase slightly. Both field observations (Shaw et al., 1990; Shaw and Zhang, 1992) and LES (Su et al., 2000) have shown strong correlation between pressure perturbations and streamwise velocity fluctuations near the forest floor. Budget analyses of the horizontal velocity variances show that the

velocity–pressure-gradient covariance is a more significant source than the vertical turbulent transport near the forest floor (Su et al., 1998a).

In general, the relative turbulence intensities ($\sigma_u(z)/U(z)$, $\sigma_v(z)/U(z)$, $\sigma_w(z)/U(z)$) are the greatest in unstable conditions and the smallest in stable conditions in both the open and closed canopies (Fig. 9b). They are also greater in the closed canopy than in the open canopy in unstable conditions, which is also the case in $z/h = 1$–0.19 under near-neutral stability and in $z/h = 1$–0.58 under stable conditions. The opposite is true at $z/h = 0.07$ in stable conditions as the secondary wind speed maximum is observed a lot more frequently in the closed canopy (84% + 9% + 4% = 97%) than in the open canopy (20%). Shaw et al. (1988) showed that in the upper part ($0.33 < z/h < 1$) of a deciduous forest, $\sigma_u(z)/U(z)$ and $\sigma_w(z)/U(z)$ are greater in the fully leafed canopy than the defoliated canopy in near-neutral conditions, and $\sigma_w(z)/U(z)$ is smaller in stable than near-neutral conditions in both leafed and defoliated canopies, which agree with our observations.

In the open canopy, $\sigma_u(z)/U(z)$ and $\sigma_v(z)/U(z)$ increase with increasing depth into the forest in all three stability categories. This is the case for $\sigma_w(z)/U(z)$ down to $z/h = 0.19$ in near-neutral and unstable conditions and to $z/h = 0.58$ in stable conditions, below which the opposite is observed. In the closed canopy, $\sigma_u(z)/U(z)$ and $\sigma_v(z)/U(z)$ generally increase with increasing depth into the forest but with two exceptions. One is the peak $\sigma_u(z)/U(z)$ at $z/h = 0.58$ in near-neutral stability, and the other is the reversal in both $\sigma_u(z)/U(z)$ and $\sigma_v(z)/U(z)$ from $z/h = 0.19$ to 0.07 in stable conditions due to more frequent occurrences of the secondary wind speed maximum at $z/h = 0.07$ in stable (97%) than in near-neutral (52% + 7% = 59%) and unstable (46% + 15% = 61%) conditions. On the other hand, there are two peaks in $\sigma_w(z)/U(z)$ at $z/h = 0.58$ and 0.19. Shaw et al. (1988) also observed peaks in both $\sigma_u(z)/U(z)$ and $\sigma_w(z)/U(z)$ at $z/h = 0.6$ below the level of maximum LAD in near-neutral stability, which are more pronounced in leafed than defoliated canopies. They showed that the peak in $\sigma_w(z)/U(z)$ is more prominent in near-neutral stability than in stable conditions, which also agree with our observations. These results indicate that both canopy morphology and stability have significant impacts on the relative turbulence intensities inside forest canopies.

3.5. The zero-plane displacement height

The zero-plane displacement height (d) is commonly used to modify the logarithmic wind profile over rough-wall boundary layers $U(z) = (u_*/\kappa) \ln[(z - d)/z_0]$, where z_0 is the roughness length and $\kappa = 0.4$ is the von Karman constant. Measurements in a wind tunnel (Thom, 1971) reported that d determined from wind profiles above an artificial crop matches the effective level the mean drag appears to act, which corresponds to the level of mean momentum absorption in the absence of an external horizontal pressure-gradient force (Jackson, 1981). In a horizontally homogeneous canopy, the momentum absorption may be estimated as the vertical divergence of Reynolds stress $u_*^2(z)$, we have:

$$d = \frac{\int_0^h z(\partial u_*^2(z)/\partial z)\,dz}{\int_0^h (\partial u_*^2(z)/\partial z)\,dz}. \tag{1}$$
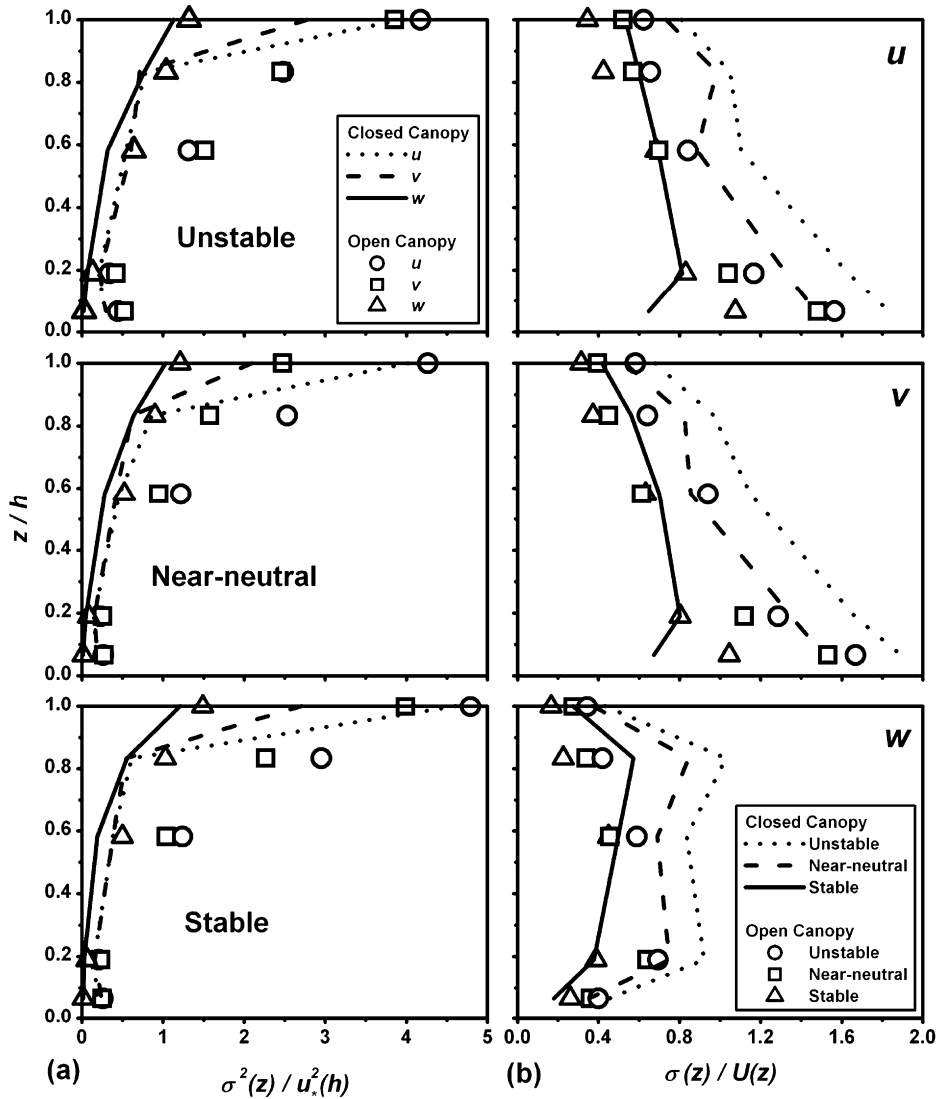
Fig. 9 – Ensemble averaged (a) normalized velocity variances; (b) relative turbulence intensities.

Based on the measured vertical profiles of $u_*^2(z)/u_*^2(h)$ (Fig. 8a), it is reasonable to assume that $u_*^2(z)$ is approximately zero at the ground surface inside forests. At the latitude of UMBS forest, the kinematic external horizontal pressure-gradient force corresponding to a geostrophic wind of 25 m s^{-1} is an order of magnitude smaller than ensemble averaged $u_*^2(h)/h$ in near-neutral stability. Thus, it is also reasonable to assume that the effect of a non-zero external horizontal pressure-gradient force on the estimate of d is small.

At UMBS, the influence of canopy morphology on d is much greater than those of thermal stability (Fig. 10a) and wind speed (Fig. 10b). An elevated d for the closed canopy than the open canopy is expected since seasonal differences in VAD are the greatest in the upper part of the forest (Fig. 1b) where a relatively larger percentage of momentum is absorbed in the closed canopy than in the open canopy (Fig. 8a). This agrees with Shaw and Pereira (1982) in that d increases monotonically not only with increasing VAI, but also as the level of maximum VAD moved upward.

In near-neutral stability, the ensemble averaged d is $0.65h$ for the open canopy and $0.81h$ for the closed canopy (Fig. 10a). It is elevated to $0.7h$ and $0.87h$ for the open and closed canopies respectively in stable conditions. This may also be explained as the depth of momentum penetration decreases, a relatively greater percentage of momentum is absorbed in the upper canopy (Fig. 8a). Similarly, differences in d between unstable and near-neutral conditions are small since the differences in $u_*^2(z)/u_*^2(h)$ are small.

We use measurements in near-neutral stability to examine the influence of wind speed (Fig. 10b). For the open canopy, there is no clear dependence of d on the mean wind speed even though the observations used here do not include hourly runs with $U(h) < 1.2 \text{ m s}^{-1}$. But for the closed canopy, ensemble averaged d decreases with increasing wind speed with an averaged value of $0.83h$ for $U(h) < 1.4 \text{ m s}^{-1}$ and $0.79h$ for $U(h) > 3 \text{ m s}^{-1}$. This is also because in near-neutral stability, momentum penetrates deeper into the forest at higher wind speeds. Other factors that may facilitate deeper penetration of momentum include streamlining of individual shoots with
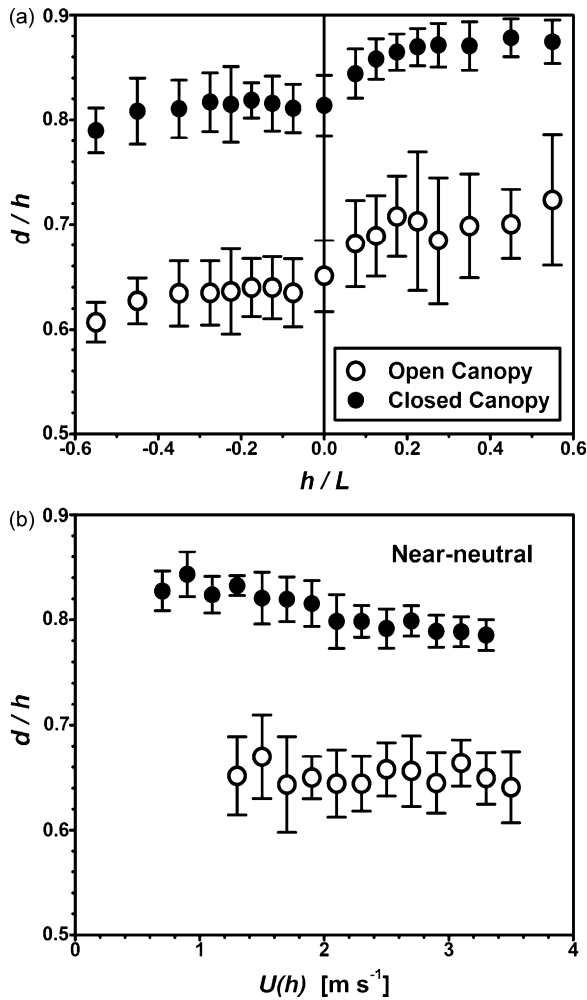
(a)

(b)

Fig. 10 – Influences of canopy morphology, thermal stability (a) and wind speed (b) on the zero-plane displacement height d.

increasing wind speed (Thom, 1971; Monteith and Unsworth, 1990) and bending of fully leafed crowns of mature aspen trees during gusty winds. Estimates of d based on measurements of mean wind profiles in and above a bean crop (Thom, 1971) and a Douglas fir plantation (Bosveld, 1997) also decrease with increasing wind speed. A difference between these two earlier studies is that Thom (1971) calculated d as the level of action of the drag force using a constant drag coefficient, whereas Bosveld (1997) estimated d based on non-dimensional wind shear measured above the forest and empirical flux-gradient relationship derived for the inertial surface layer based on the Monin–Obukhov similarity theory (Dyer, 1974).

In near-neutral stability, our earlier estimates based on CSAT3 measurements at two levels ($z/h = 1.5$ and 2.1) on the main AmeriFlux tower and the modified logarithmic wind profile (Su et al., 2004) also yielded smaller d for the open canopy ($0.6h$) than the closed canopy ($0.75h$), but are smaller (by $0.05h$ and $0.06h$) than the current estimates using Eq. (1). A problem using measured wind profiles to estimate d is that the results vary with height in the roughness sublayer above the canopy where the mean wind profile is not logarithmic (Shaw and Pereira, 1982; Raupach et al., 1986; Su et al., 1998b). The

differences between d estimated using wind speed at twice the canopy height and that as the effective level of mean drag vary with vegetation density, and can be as large as $0.1h$ (Shaw and Pereira, 1982). Furthermore, an independent estimate of d such as Eq. (1) may be useful in examining departures of the flux-gradient relationship in the roughness sublayer from those obtained from observations over smooth surfaces in all diabatic conditions, and subsequent efforts to modify them to estimate fluxes based on profile measurements over forest canopies (Bosveld, 1997).

3.6. Drag coefficients

First, we use measurements at the canopy top to calculate the bulk drag coefficient, $C_D^h = u_*^2(h)/U^2(h)$, which is a measure of the overall efficiency of the forest in absorbing momentum for a given wind speed. At UMBS, C_D^h is much greater over the closed canopy than the open canopy in all classes of h/L with values of 0.137 and 0.064 in near-neutral stability (Fig. 11a). In comparison, Shaw et al. (1988) reported that the influence of LAI is small with C_D^h of 0.092, 0.102 and 0.094 for LAI = 4.9, 1.6 and 0.3 in near-neutral stability. We also calculated C_D^h using the "cup" wind speed as in Shaw et al. (1988) and found that C_D^h remains significantly larger over the closed canopy than the open canopy with values of 0.083 and 0.055 in near-neutral stability. The reduction in C_D^h using the "cup" wind speed is greater for the closed canopy due to higher relative turbulence intensities (Fig. 9b). Since the vegetation density is not explicitly accounted for in calculating C_D^h, we normalize it with VAI and found that there is little difference in $C_{D*}^h = C_D^h/\text{VAI}$ between the closed and open canopies with a value of about 0.03 in near-neutral stability (Fig. 11b). Obviously, the same normalization would not work for the results reported by Shaw et al. (1988) despite that they used LAI in their discussion. But our observations agree with Shaw et al. (1988) in regard to the stability effect such that the bulk drag coefficient decreases with increasing stability.

Second, we calculate the mean drag coefficient for the entire forest (C_d^m) following Thom (1971):

$$C_d^m = \frac{u_*^2(h)}{\int_0^h \text{VAD}(z) \cdot U^2(z)\, dz} = \frac{u_*^2(h)}{\text{VAI} \cdot U_m^2} \tag{2}$$

where U_m^2 is a weighted mean of $U^2(z)$ by $\text{VAD}(z)/\text{VAI}$ over the entire canopy.

An analogy between C_{D*}^h and C_d^m can be made by

$$\frac{u_*^2(h)}{h} = C_{D*}^h \frac{\text{VAI}}{h} U^2(h) = C_d^m \frac{\text{VAI}}{h} U_m^2 \tag{3}$$

where the left-hand-side approximates the mean vertical divergence of Reynolds stress over the entire canopy assuming $u_*^2(z)$ at the ground is zero. The middle and right parts of Eq. (3) are in a form of typical parameterization of drag force in which VAI/h is the mean vegetation density of the entire forest. Obviously, the ratio

$$\frac{C_{D*}^h}{C_d^m} = \frac{U_m^2}{U^2(h)} = \int_0^h \frac{\text{VAD}(z)}{\text{VAI}} \frac{U^2(z)}{U^2(h)}\, dz \tag{4}$$
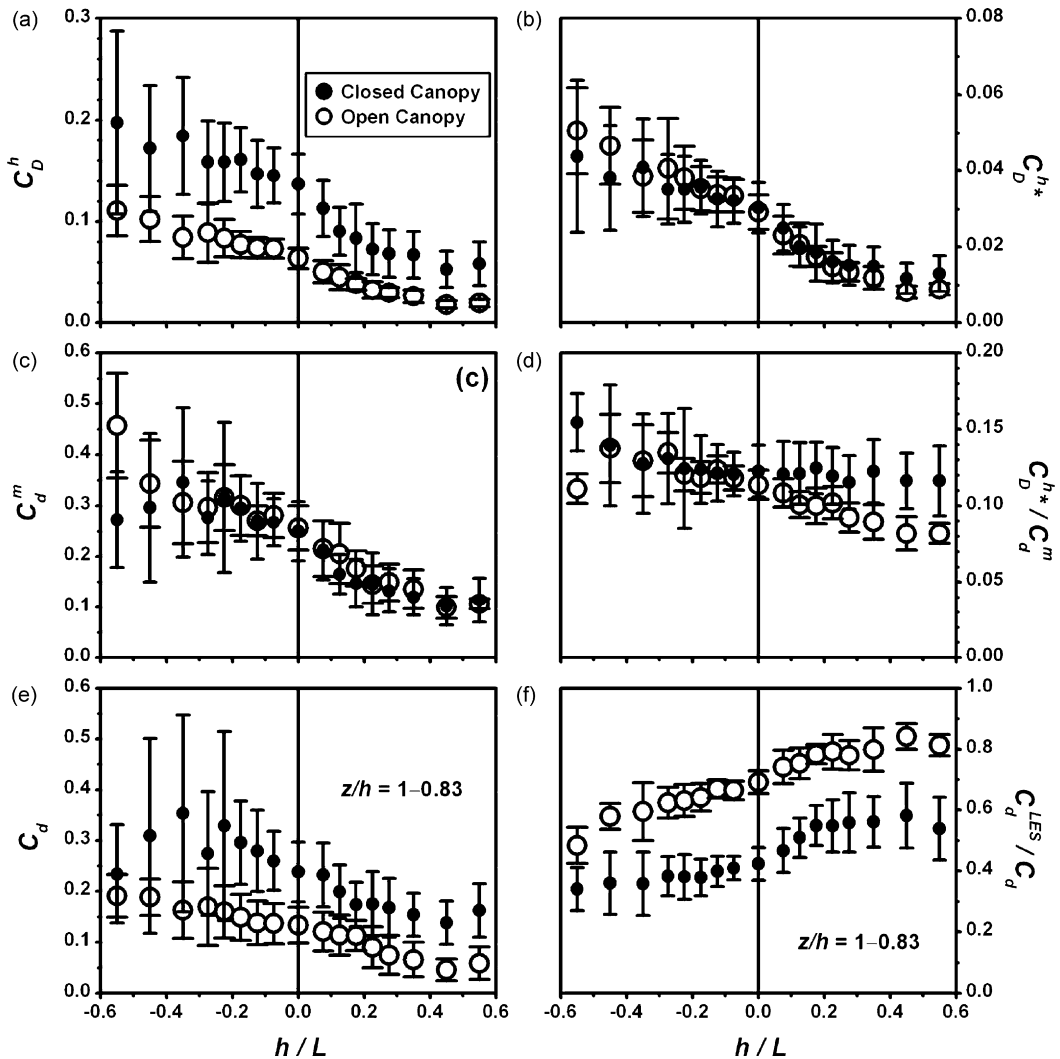
Fig. 11 – Influences of canopy morphology and thermal stability on drag coefficients and their ratios.

is less than unity since U_m takes into account of attenuation of wind speed inside canopy and is smaller than $U(h)$. In addition, this ratio may vary with both canopy morphology (vertical profile of VAD(z)/VAI) and thermal stability, both of which influence the vertical profile of $U^2(z)/U^2(h)$.

Similar to C_D^{h*}, C_d^m decreases with increasing stability, and there is little difference in C_d^m between the closed and open canopies with a value of about 0.25 in near-neutral stability (Fig. 11c). Differences in C_D^h*/C_d^m between the open and closed canopies in near-neutral and unstable conditions are also negligible (Fig. 11d) despite large differences in the vertical profiles of VAD(z)/VAI (Fig. 1b) and $U^2(z)/U^2(h)$ (Fig. 6). In near-neutral stability, C_D^h*/C_d^m has a value of about 0.11–0.12, which is close to 0.13 found for an artificial crop in a wind tunnel experiment (Thom, 1971). With increasing stability, C_D^h*/C_d^m remains about the same for the closed canopy but decreases for the open canopy. One reason could be that $U^2(z)/U^2(h)$ is smaller in stable conditions than in near-neutral stability at all depths of the open canopy but only in the upper part of the closed canopy, while the opposite is true near the forest floor in the closed canopy (Fig. 6).

Third, we calculate the mean drag coefficient (C_d) for different layers of the forest to examine its vertical variations and differences between the closed and open canopies. This drag coefficient is needed to parameterize the mean drag force at a given depth inside a plant canopy, $F_d(z) = C_d \cdot VAD(z) \cdot U^2(z)$, which is included in the mean momentum budget equation in multi-layer closure models (Wilson and Shaw, 1977; Raupach and Thom, 1981; Meyers and Paw U, 1986; Wilson, 1988; Lee et al., 1994; Katul et al., 2004). Assuming horizontal homogeneity and a balance between the mean drag force and the vertical divergence of Reynolds stress, we may estimate C_d using measured vertical profiles of Reynolds stress, mean wind speed and VAD (Raupach and Thom, 1981; Amiro, 1990b; Su et al., 1998b):

$$C_d = \frac{\partial u_*^2(z)/\partial z}{VAD(z) \cdot U^2(z)}, \tag{5}$$

where the total tangential Reynolds stress $u_*^2(z)$ and the vector mean wind speed $U(z)$ are used due to the horizontal mean wind directional shear. Similar to Mahrt et al. (2000), to reduce

the effects of random measurement errors, we excluded hourly runs with $u_*^2(z) < 1 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$. In addition, because the vertical divergence of Reynolds stress is often quite small between the lowest two measurement levels ($z/h = 0.19–0.07$) (Fig. 8), we excluded hourly runs with $\partial u_*^2(z)/\partial z < 6 \times 10^{-3} \text{ m s}^{-2}$. This threshold is determined by $u_*^2(h)/h$ with $u_*(h) = 0.35 \text{ m s}^{-1}$ as airflow inside the forest is found to be well-mixed in nocturnal stable conditions when $u_*(h) > 0.35 \text{ m s}^{-1}$ (Schmid et al., 2003). It essentially excludes hourly runs with a secondary wind speed maximum and ensures the vertical divergence of Reynolds stress is much greater than the horizontal pressure-gradient force in the mean momentum budget.

Finally, a drag coefficient (C_d^{LES}) is also needed to parameterize the instantaneous grid-volume averaged drag force, $f_i = C_d^{\text{LES}} \cdot \text{VAD} \cdot V \cdot v_i$, which is included in the filtered prognostic momentum equations in LES of airflows inside plant canopies (Shaw and Schumann, 1992). Here $V = \sqrt{u^2 + v^2 + w^2}$ is the instantaneous wind speed, and $v_i = u, v, w$ are velocity components corresponding to directional index $i = x, y, z$. Using the same assumptions for calculating C_d and setting the mean drag force equal to the time average of the instantaneous horizontal drag force $f_{xy} = \sqrt{f_x^2 + f_y^2}$ (Wilson, 1988), we can estimate C_d^{LES} as

$$C_d^{\text{LES}} = \frac{\partial u_*^2(z)/\partial z}{\text{VAD}(z)\sqrt{\left\{U^2(z) + \sigma_u^2(z) + 0.5[\sigma_v^2(z) + \sigma_w^2(z)]\right\}^2 + \left\{\overline{u'v'}(z)\right\}^2}} \tag{6}$$

Thus, C_d^{LES} is smaller than C_d for turbulent flow (Su et al., 1998b) and the ratio C_d^{LES}/C_d decreases with increased relative turbulence intensities.

Both C_d and C_d^{LES} for different layers of the closed and open canopies also decrease with increasing stability, although only the variations of C_d and C_d^{LES}/C_d with h/L in the top layer ($z/h = 1–0.83$) are shown for the sake of brevity. C_d in this layer is significantly greater in the closed canopy than in the open canopy in all classes of h/L with values of 0.238 and 0.133 in near-neutral conditions (Fig. 11e). A value of $C_d = 0.2$ was previously reported in a fully leafed aspen forest (LAI = 4) (Amiro, 1990b) and in the upper part of a partially defoliated (LAI = 2) deciduous forest (Su et al., 1998b) in near-neutral conditions, but LAI is used in these earlier estimates.

For the same stability, the ratio C_d^{LES}/C_d in the top canopy layer is smaller in the closed canopy than in the open canopy (Fig. 11f) due to greater relative turbulence intensities in the closed canopy (Fig. 9b). Thus differences in C_d^{LES} between the closed and open canopies are smaller than those in C_d. In near-neutral stability, C_d^{LES}/C_d is 0.42 for the closed canopy and 0.69 for the open canopy. In the upper part of a partially defoliated deciduous forest (LAI = 2), C_d^{LES}/C_d is about 0.75 in near-neutral conditions (Su et al., 1998b), which is closer to that for the open canopy than for the closed canopy at UMBS. Similarly, C_d^{LES}/C_d in the top canopy layer increases with increasing stability due to reduced relative turbulence intensities.

Shaw et al. (1988) state that the decrease of bulk drag coefficient with increasing stability could be argued as a consequence of a decrease in the drag coefficient of individual canopy elements at lower wind speeds which accompany

nocturnal conditions, rather than the action of atmospheric stability on vertical mixing of momentum. They showed that in near-neutral stability, the bulk canopy drag coefficient has no obvious dependence on wind speed, but it was also pointed out that observations included in their analysis do not exhibit extremely low wind speeds at the canopy top found under stable conditions. Thus, we examine the variations of C_{D*}^h with $U(h)$ separately in near-neutral and stable conditions, and comapre them in the same plot.

Over the open canopy (Fig. 12a), our observations also show that there is no clear dependence of C_{D*}^h on $U(h)$, not only in near-neutral but also in stable conditions, although we do not have hourly runs with $U(h) < 1 \text{ m s}^{-1}$. Over the closed canopy (Fig. 12b), we have only 15 hourly runs in the range of $0.6 \text{ m s}^{-1} < U(h) < 1 \text{ m s}^{-1}$ in near-neutral conditions, which show an average of 25% reduction in C_{D*}^h compared to the averaged value with $U(h) > 1 \text{ m s}^{-1}$. In contrast, we have 92 hourly runs in the range of $0.4 \text{ m s}^{-1} < U(h) < 1 \text{ m s}^{-1}$ in stable conditions with an averaged C_{D*}^h about 25% higher than the averaged value in the highest range of observed $U(h) = 1.4–1.6 \text{ m s}^{-1}$. In addition, for the same wind speed when $U(h) > 1 \text{ m s}^{-1}$, C_{D*}^h in stable conditions is reduced about 60% from that in near-neutral conditions over both the open and closed canopies. Despite the opposite changes in C_{D*}^h at low wind speeds in near-neutral and stable conditions over the closed canopy, C_{D*}^h in stable conditions is still smaller than that in near-neutral conditions when $0.6 \text{ m s}^{-1} < U(h) < 1 \text{ m s}^{-1}$.

Similarly, C_d in the top canopy layer ($z/h = 1–0.83$) in stable conditions is greatly reduced from that in near-neutral conditions for the same mean wind speed $U(z)$ in both the open (Fig. 12c) and closed (Fig. 12d) canopies. This is also the case for the other layes of the forest although they are not shown here for the sake of brevity. These results indicate that suppressed vertical mixing of momentum is primarily responsible for the reduced drag coefficeint in stable conditions. This is not unexpected since the vertical divergence of Reynolds stress is used as a measure of momentum absorption (drag force) in the estimates of all drag coefficients presented here. Therefore, we focus our discussions on the vertical variations of C_d and its dependence on wind speed in near-neutral stability.

Earlier we have shown that in near-neutral stability, C_d^m is about the same (0.25) for the open and closed canopies (Fig. 11c), but C_d for the top layer ($z/h = 1–0.83$) is 79% greater in the closed canopy (0.238) than the open canopy (0.133) (Fig. 11e). This indicates that the effective drag coefficients of the bigtooth aspen leaves (which accounting for 87% of total vegetation area in this layer) is greater than that of the bare branches and twigs, even though the drag coefficient for a single leaf is likely even greater due to shelter effect. In contrast, C_d for the layer $z/h = 0.83–0.58$ is 53% greater in the open canopy (0.550) than in the closed canopy (0.359), which indicates that the effective drag coefficient of the bare trunks of aspen trees must be significantly greater than that of the deciduous leaves. Below $z/h = 0.58$, it becomes more difficult to relate C_d to individual vegetation elements because of the complex composition of vegetation species with various heights. Among the 2158 trees with diameter at breast height DBH > 3×10^{-2} m that are measured in a $1.1 \times 10^4 \text{ m}^2$ study
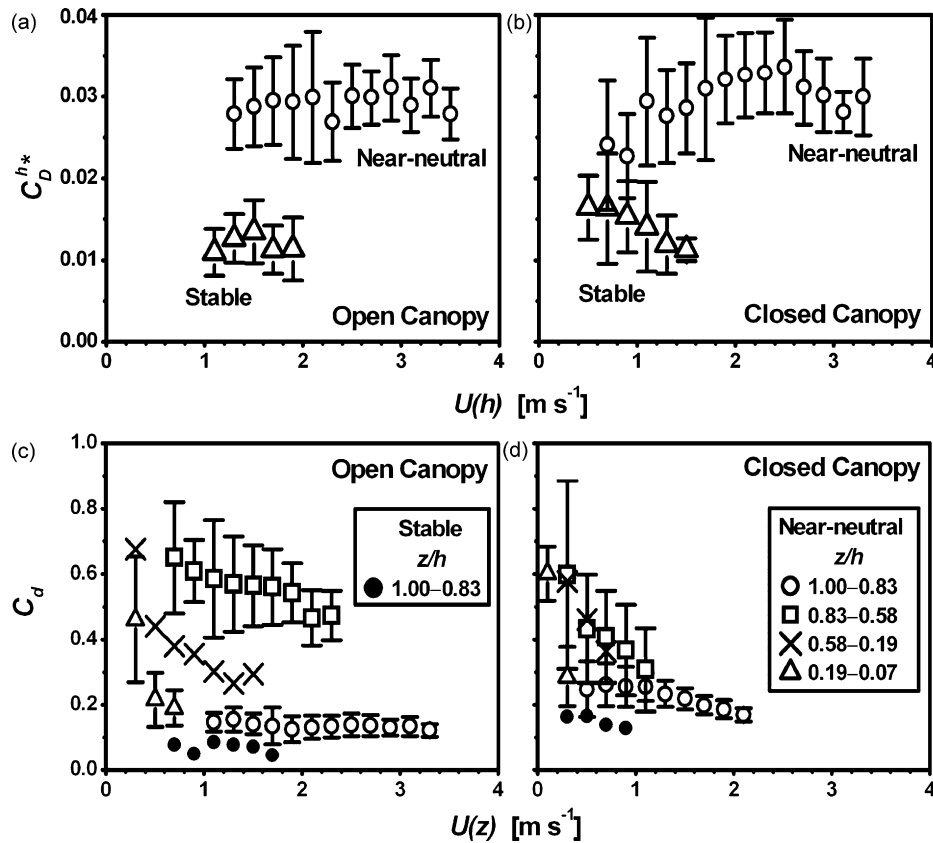
Fig. 12 – Influences of thermal stability and wind speed on drag coefficients and their vertical variations inside the canopy.

plot near the tower in the upwind directions (Bovard, 2005), 14% are aspen trees (only bare trunks below $z/h = 0.58$), 24% are other deciduous species (red maple, paper birch and red oak) with an average tree height of $0.55h$, 60% are young white pines with a mean height of $0.27h$ and 2% are American beech with a mean height of $0.34h$.

In general, C_d for the same canopy layer increases with decreasing local mean wind speed, except for the top layer in the open canopy where observations used here do not include hourly runs with $U(z) < 1 \text{ m s}^{-1}$. This agrees with the drag coefficient for a rigid circular cylinder (10^{-3} m in diameter) measured in a wind tunnel experiment (Thom, 1971). The largest values (0.651–0.609) of C_d we found for $z/h = 0.83$–0.58 in the open canopy are quite close to the values (0.8–0.7) found for the rigid circular cylinder at the same range of wind speeds (0.6–1.0 m s^{-1}), even though the characteristic length scales of vegetation elements in this layer and thus the Renolds number are much greater in the UMBS forest. Finally, since mean wind speed decreases with increasing depth into the forest, the vertical variations of C_d may also change with wind speed.

3.7. Eddy-diffusivity and mixing-lengths

A well-known deficiency of first- and 1.5-order closure models that use down-gradient diffusion is their inability to reproduce observed counter-gradient flux in plant canopies. One of the main reasons for the continued use of these models is that

they are computationally more efficient than higher-order closure models. In addition, Katul et al. (2004) showed that when the mixing length is *a priori* specified, a 1.5-order model estimates mean wind speed, turbulence kinetic energy (TKE) and Reynolds stress no worse than published values estimated by second- and third-order closure models in a variety of plant canopies, although their model failed to reproduce observed secondary wind speed maximum. On the other hand, Lee et al. (1994) showed that a first-order mixing-length model (Li et al., 1985) can produce a secondary wind speed maximum when a mean horizontal pressure-gradient force is included, but the model cannot reproduce counter-gradient momentum flux.

Here we use measured vertical profiles of Reynolds stress and mean wind speed to estimate the eddy-diffusivity for momentum inside the forest as

$$K_M(z) = \frac{u_*^2(z)}{\partial U(z)/\partial z}.$$ (7)

At the canopy top, we use the formula $K_M(h) = \kappa \cdot u_*(h) \cdot (h - d)$ (Kaimal and Finnigan, 1994). The results of Lee et al. (1994) indicate that when the mean horizontal pressure-gradient force is a more important source of mean momentum than the vertical divergence of Reynolds stress inside plant canopies, there may be little relation between local vertical gradient of mean wind speed and momentum flux, and non-local transport of momentum (downward flux) can be in the direction of increasing mean wind speed (secondary wind

speed maximum). Therefore, for simplicity, we only present ensemble averaged estimates of $K_M(z)$ based on hourly runs corresponding to Group-1 ($\partial U(z)/\partial z > 0$) of the mean wind speed profiles (Fig. 6a and b). An exception is under stable conditions in the closed canopy, for which the estimates are averaged over hourly runs corresponding to Group-2 because they constitute the majority of hourly observations, but results between the lowest two measurement levels where $\partial U(z)/\partial z < 0$ and thus estimated $K_M(z) < 0$ are excluded. In addition, hourly runs with $u_*^2(z) < 1 \times 10^{-4}\,\mathrm{m^2\,s^{-2}}$ and $\partial U(z)/\partial z < 1 \times 10^{-2}\,\mathrm{s^{-1}}$ are excluded to reduce the effects of random measurement errors.

A mixing-length and a velocity scale are needed to parameterize $K_M(z)$. Wilson and Shaw (1977) and Li et al. (1985) assume that the mixing-length decreases with increasing depth into the forest and is smaller for greater VAD. On the other hand, Massman and Weil (1999) and Katul et al. (2004) assume constant mixing-length inside plant canopies. Here we estimate

the effective mixing-lengths for three velocity scales: $u_*(z)$ (Thom, 1971; Lee et al., 1994), $\sigma_w(z)$ (Goudriaan, 1977), and $e^{1/2}(z) = [0.5(\sigma_u^2(z) + \sigma_v^2(z) + \sigma_w^2(z))]^{1/2}$ (Katul et al., 2004).

$$K_M(z) = \begin{cases} L_1(z) \cdot u_*(z) \\ L_2(z) \cdot \sigma_w(z) \\ L_3(z) \cdot e^{1/2}(z) \end{cases} = \begin{cases} \alpha_1(z) \cdot h \cdot u_*(z) \\ \alpha_2(z) \cdot h \cdot \sigma_w(z) \\ \alpha_3(z) \cdot h \cdot e^{1/2}(z) \end{cases}, \quad (8)$$

where $L_1(z)$, $L_2(z)$, $L_3(z)$ are corresponding effective mixing lengths and $\alpha_1(z)$, $\alpha_2(z)$, $\alpha_3(z)$ are their normalizations by the mean canopy height h. At the canopy top, we use $L_1(h) = \kappa \cdot (h - d)$, $L_2(h) = \kappa \cdot (h - d) \cdot u_*(h)/\sigma_w(h)$ and $L_3(h) = \kappa \cdot (h - d) \cdot u_*(h)/e^{1/2}(h)$. Katul et al. (2004) determined $\alpha_3(z)$ by matching (continuity) $\alpha_3(z) \cdot h$ to $\kappa \cdot (h - d)$ at the canopy top. However, they used $e^{1/2}(z)$ inside the canopy but $u_*(h)$ at the canopy top and above in parameterizing $K_M(z)$, thus a factor of $u_*(h)/e^{1/2}(h)$ should be taken into account in the matching process. This factor would vary with canopy morphology and stability (Fig. 9a).
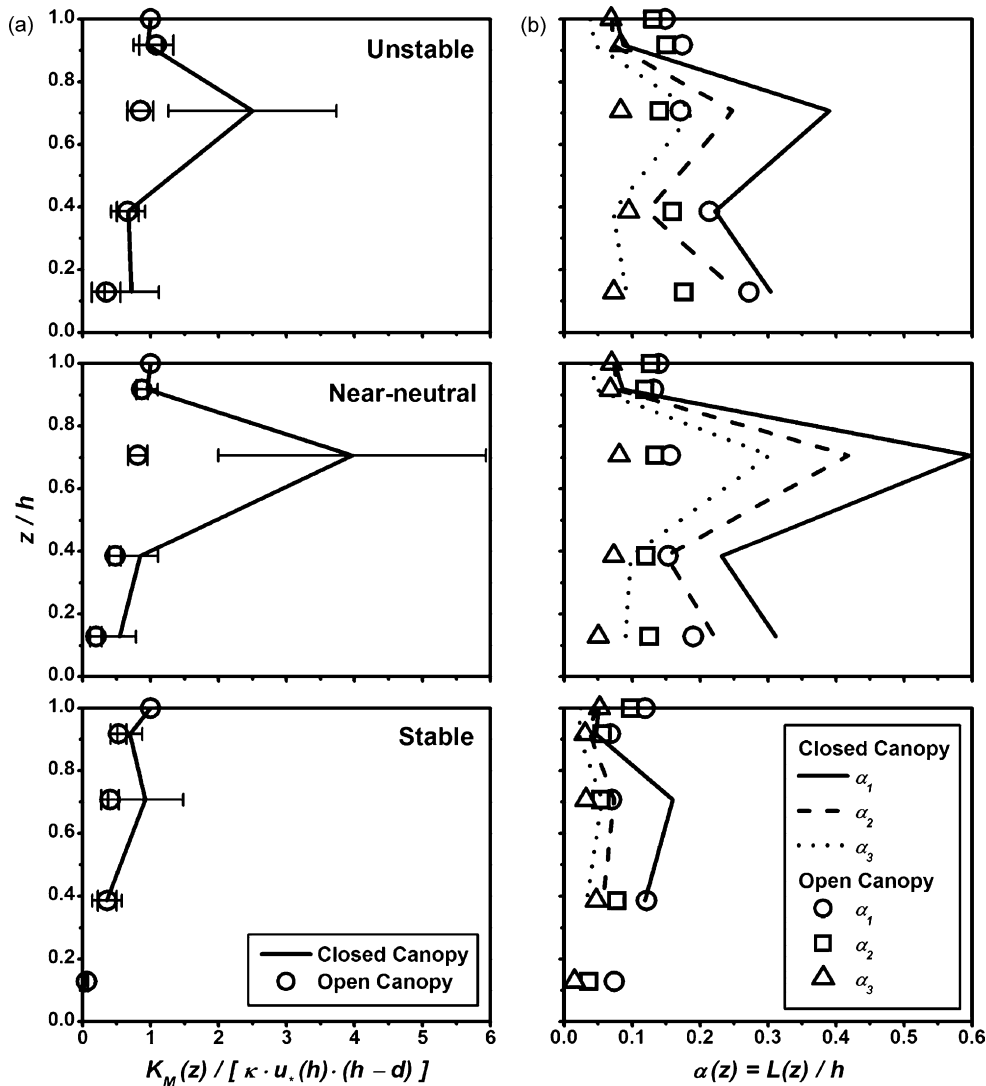

Fig. 13 – (a) Normalized eddy-diffusivity for momentum transfer $K_M(z)/[\kappa \cdot u_*(h) \cdot (h - d)]$; (b) comparison of normalized mixing-lengths $\alpha(z) = L(z)/h$ with different velocity scales. The profiles are averaged over hourly runs corresponding to Group-1 of the mean wind speed profiles in Fig. 6, except that Group-2 are used for stable conditions in the closed canopy as they are the majority of hourly observations.

The most noticeable feature in normalized eddy-diffusivity $K_M(z)/[\kappa \cdot u_*(h) \cdot (h-d)]$ (Fig. 13a) and mixing-lengths $\alpha(z) = L(z)/h$ (Fig. 13b) is the peaks (most and least pronounced in near-neutral and stable conditions) with the greatest standard deviations at $z/h = 0.71$ below the crowns of mature aspen trees in the closed canopy, which are absent in the open canopy. This could be in part due to the fact that $\partial U(z)/\partial z$ in $z/h = 0.83$–0.58 is much smaller than that in $z/h = 1$–0.83 in the closed canopy, whereas the difference in $\partial U(z)/\partial z$ between the two layers are much smaller in the open canopy (Fig. 6). These peaks are likely another example (in addition to counter-gradient flux) of non-local transport rather than enhanced eddy-diffusivity and increased mixing-lengths at $z/h = 0.71$ compared to those at $z/h = 0.92$ and the canopy top. Removing the peaks from the picture (Fig. 13a), the normalized eddy-diffusivity generally decreases with increasing depth into both the open and closed canopies, and also decreases with increasing stability.

All three mixing-lengths decrease with increasing stability but $\alpha_1(z) > \alpha_2(z) > \alpha_3(z)$ at the same height in both the open and closed canopies for the same stability category (Fig. 13b). However, the estimated mixing-lengths at $z/h = 0.92$ and at the canopy top are greater in the open canopy than in the closed canopy in all three stability categories, whereas the opposite is true at $z/h = 0.71$ and below in near-neutral and unstable conditions. As such, the vertical variations in estimated mixing-lengths are smaller in the open canopy than in the closed canopy. Particularly in near-neutral stability, $\alpha_2(z)$ is pretty constant with height throughout the open canopy with an average value of 0.125, and the other two mixing-lengths are also quite constant from the canopy top to $z/h = 0.39$ in the open canopy with averaged vaues of $\alpha_1(z) = 0.154$ and $\alpha_3(z) = 0.069$. In comparison, Lee and Mahrt (2005) observed that $\alpha_1(z)$ is smaller in the lower canopy than in the upper canopy in an old aspen forest (0.11 at $z/h \approx 0.3$ and 0.16 at $z/h \approx 0.95$) and a pine stand (0.13 at $z/h \approx 0.2$ and 0.15 at $z/h \approx 0.7$) in near-neutral stability.

4. Conclusions

The influences of thermal stability and seasonal changes in canopy morphology on both mean flow and turbulence statistics inside the UMBS forest are examined based on a year long field experiment. Major findings summarized below are based on observations with the mean winds at the canopy top from the prevailing directions between $210°$ and $330°$, in which variations of flow statistics with azimuth are small.

Secondary wind speed maxima are not a fixed feature in this forest and the frequency of their occurrence varies with canopy morphology and stability. Our observations agree with previously observed and modeled mean wind profiles in forest canopies in that secondary wind speed maxima are located below the level(s) of peak VAD. We observed two secondary wind speed maxima in the fully leafed closed canopy which has two peaks of VAD. The secondary wind speed maximum at $z/h = 0.07$ below the level of peak VAD in the understory (young white pines) is observed more frequently and is more pronounced in the closed canopy than in the defoliated open canopy, and in stable than near-

neutral and stable conditions. In near-neutral stability, it is also more pronounced when mean wind speed at the canopy top is lower. The secondary wind speed maximum at $z/h = 0.58$ is observed only in the closed canopy below the level of peak VAD in the upper canopy (crowns of mature aspen trees), but it occurs much less frequently and is less pronounced than the secondary wind speed maximum at $z/h = 0.07$ in the same stability. Our observations differ from several earlier observations in various forests which reported that the secondary wind speed maximum is the most pronounced in unstable conditions, but agree with the predictions of a higher-order closure model. Although the horizontal mean pressure-gradient force may be the cause of the secondary wind speed maximum as suggested by previous modeling studies, our observations show that the smaller is the vertical divergence of Reynolds stress, the more pronounced is the secondary wind speed maximum.

Horizontal mean winds inside the UMBS forest are observed to flow to the left (counter-clockwise) of the mean wind at the canopy top. The degrees of turning of the horizontal mean winds generally increase with increasing depth into the forest except for a reversal (clockwise) between the lowest two measurement levels near the forest floor in the closed canopy, where the variations of measured wind directional differences are very large. In addition, the horizontal mean wind directional turn is greater in the closed canopy than in the open canopy but smaller in near-neutral than unstable and stable conditions. These results indicate that airflow in forests should be treated or modeled at least in a 2D framework (vertical and transverse) for a reference streamwise direction such as the mean wind direction at the canopy top.

The influences of canopy morphology and stability on the vertical profiles of Reynolds stress, correlation coefficient and velocity variances generally agree with earlier observations such that their attenuations with increasing depth into the forest is more rapid in the closed (denser) canopy and in stable conditions. On the other hand, the relative turbulence intensities are generally greater in the closed canopy than in the open canopy and decrease with increasing stability. Since seasonal difference in VAD between the closed and open canopies is the greatest in the top canopy layer corresponding to the crowns of mature aspen trees, its influence is greater than stability. The effect of stability in the top canopy layer is also greater in the closed canopy than in the open canopy. However, in near-neutral stability, we observed $r_{uw}(h)$ becomes more negative and $\sigma_u^2(z)/u_*^2(h)$, $\sigma_v^2(z)/u_*^2(h)$, $\sigma_w^2(z)/\sigma_w^2(h)$ decrease with increasing VAI, while earlier observations in a deciduous forest show that $r_{uw}(h)$ becomes less negative and $\sigma_u^2(h)/u_*^2(h)$ increases with increasing LAI and $\sigma_w^2(h)/u_*^2(h)$ is about the same for LAI = 0.3–4.9.

In near-neutral stability, estimated zero-plane displacement height (d) for the closed canopy decreases with increasing mean wind speed at the canopy top with an averaged value of $0.81h$ while d for the open canopy does not show a clear dependence on mean wind speed with an averaged value of $0.65h$. These values are 0.05–0.06h greater than earlier estimates using the logarithmic wind profile formula and measurements of Reynolds stress and mean wind speed at two heights above the canopy. Estimated values of d

in unstable conditions do not differ significantly from those in near-neutral stability, but increase to 0.87h and 0.7h for the closed and open canopies in stable conditions. At UMBS, the influence of canopy morphology on d is much greater than those of thermal stability and wind speed.

The bulk drag coefficient (C_D^h) measured at the canopy top is much greater over the closed canopy than the open canopy, which is contrary to earlier observations over a deciduous forest which showed that the influence of LAI is very small. Both the normalized bulk drag coefficient ($C_{D*}^h = C_D^h/\text{VAI}$) and the mean canopy drag coefficient (C_d^m) are about the same between the closed and open canopies for the same stability with values of about 0.03 and 0.25 in near-neutral stability. When the mean wind speed at the canopy height is less than $1 \, \text{m s}^{-1}$, C_{D*}^h over the closed canopy decreases by about 25% in near-neutral stability but increases by 25% in stable conditions. In near-neutral stability, estimated drag coefficient (C_d) used in the parameterization of the drag force in mean momentum budget equations in closure models varies with height and increases with decreasing wind speed, and its values at the same depth of the closed and open canopies also differ. The drag coefficient (C_d^{LES}) used in the parameterization of the drag force in prognostic momentum equations in LES of airflow inside forests is smaller than C_d. The ratio C_d^{LES}/C_d is smaller in the closed canopy than in the open canopy and increases with increasing stability, as the relative turbulence intensities are greater in the closed canopy and decrease with increasing stability. The results that C_D^h, C_{D*}^h, C_d^m, C_d and C_d^{LES} have quite different values could be significant since the bulk drag coefficient reported in Shaw et al. (1988) has been used in many different models of airflow in a variety of plant canopies, especially if the model results are sensitive to the value of a particular drag coefficient.

It is shown that all drag coefficients decrease while the displacement height increases with increasing stability. This indicates that these estimated aerodynamic parameters are not entirely the properties of the vegetation elements, but are significantly influenced by vertical turbulent mixing of momentum.

Estimated eddy-diffusivity and mixing-lengths corresponding to three different velocity scales for momentum transfer decrease with increasing stability in both the closed and open canopies. An evidence of non-local transport is illustrated by the peak values of eddy-diffusivity and mixing-lengths below the crowns of mature aspen trees in the closed canopy. Otherwise, the eddy-diffusivity generally decreases with increasing depth into the forest. On the other hand, the mixing-lengths above the level of the peaks are greater in the open canopy than in the closed canopy in all three stability categories, whereas the opposite is true below the level of the peaks in near-neutral and unstable conditions. Overall, the mixing-lengths are relatively more constant with height in the open canopy than in the closed canopy.

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REFERENCES

Albini, F.A., 1981. A phenomenological model for wind speed and shear stress profiles in vegetation cover layers. J. Appl. Meteorol. 20, 1325–1335.

Allen, L.H., 1968. Turbulence and wind speed spectra within a Japanese larch plantation. J. Appl. Meteorol. 7, 73–78.

Amiro, B.D., 1990a. Comparison of turbulence statistics within three Boreal forest canopies. Boundary-Layer Meteorol. 51, 99–121.

Amiro, B.D., 1990b. Drag coefficients and turbulence spectra within three Boreal forest canopies. Boundary-Layer Meteorol. 52, 227–246.

Ayotte, K.W., Finnigan, J.J., Raupach, M.R., 1999. A second-order closure for neutrally stratified vegetation canopy flows. Boundary-Layer Meteorol. 90, 189–216.

Baldocchi, D.D., Hutchison, B.A., 1987. Turbulence structure in a deciduous forest. Boundary-Layer Meteorol. 43, 345–364.

Baldocchi, D.D., Meyers, T.P., 1988. Turbulence in an almond orchard: vertical variation in turbulence statistics. Boundary-Layer Meteorol. 40, 127–146.

Baldocchi, D.D., Finnigan, J.J., Wilson, K.B., Paw U, K.T., Falge, E., 2000. On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Boundary-Layer Meteorol. 96, 257–291.

Bosveld, F.C., 1997. Derivation of fluxes from profiles over a moderately homogeneous forest. Boundary-Layer Meteorol. 84, 289–327.

Bovard, B.D., 2005. Environmental controls on sap flow in a northern hardwood forest. Tree Physiol. 25, 31–38.

Cionco, R.M., 1965. A mathematical model for air flow in a vegetative canopy. J. Appl. Meteorol. 4, 517–522.

Dyer, A.J., 1974. A review of flux–profile relationships. Boundary-Layer Meteorol. 7, 363–372.

Finnigan, J.J., 2000. Turbulence in plant canopies. Annu. Rev. Fluid Mech. 32, 519–571.

Finnigan, J.J., Clements, R., Malhi, Y., Leuning, R., Cleugh, H.A., 2003. A re-evaluation of long-term flux measurement techniques. Part I. Averaging and coordinate rotation. Boundary-Layer Meteorol. 107, 1–48.

Finnigan, J.J., 2004. A re-evaluation of long-term flux measurement techniques. Part II. Coordinate systems. Boundary-Layer Meteorol. 113, 1–41.

Fons, W.L., 1940. Influence of forest cover on wind velocity. J. Forestry 38, 481–486.

Garratt, J.R., 1992. The Atmospheric Boundary Layer. Cambridge University Press, Cambridge, UK, 316 pp.

Goudriaan, J., 1977. Crop Micrometeorology: A Simulation Study. Center for Agricultural Publishing and Documentation, Wageningen, The Netherlands, 249 pp.

Inoue, E., 1963. On the turbulent structure of airflow within crop canopies. J. Meteorol. Soc. Jpn. 41, 317–326.

Jackson, P.S., 1981. On the displacement height in the logarithmic velocity profile. J. Fluid Mech. 111, 15–25.

Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, UK, 289 pp.

Katul, G.G., Albertson, J.D., 1998. An investigation of higher-order closure models for a forested canopy. Boundary-Layer Meteorol. 89, 47–74.

Katul, G.G., Mahrt, L., Poggi, D., Sanz, C., 2004. One- and two-equation models for canopy turbulence. Boundary-Layer Meteorol. 113, 81–109.

Kondo, J., Akashi, S., 1976. Numerical studies on the two-dimensional flow in horizontal homogeneous canopy layer. Boundary-Layer Meteorol. 10, 255–272.

Landsberg, J.J., James, G.B., 1971. Wind profiles in plant canopies: studies on an analytical model. J. Appl. Ecol. 8, 729–741.

Leclerc, M.Y., Beissner, K.C., Shaw, R.H., den Hartog, G., Neumann, H.H., 1990. The influence of atmospheric stability on the budgets of the Reynolds stress and turbulent kinetic energy within and above a deciduous forest. J. Appl. Meteorol. 29, 916–933.

Leclerc, M.Y., Beissner, K.C., Shaw, R.H., den Hartog, G., Neumann, H.H., 1991. The influence of foliage buoyancy on third-order turbulent velocity statistics within a deciduous forest. Boundary-Layer Meteorol. 55, 109–123.

Lee, X., Black, A., 1993. Atmospheric turbulence within and above a Douglas-fir stand. Part I. Statistical properties of the velocity field. Boundary-Layer Meteorol. 64, 149–174.

Lee, X., Shaw, R.H., Black, A., 1994. Modelling the effect of mean pressure gradient on mean flow within forests. Agric. For. Meteorol. 68, 201–212.

Lee, X.-H., 1998. On micrometeorological observations of surface-air exchange over tall vegetation. Agric. For. Meteorol. 91, 39–49.

Lee, X., Finnigan, J., Paw U, K.T., 2004. Coordiate systems and flux bias error. In: Lee, X., Massman, W.J., Law, B. (Eds.), Handbook of Micrometeorology – A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, pp. 33–66 (250 pp.).

Lee, Y.-H., Mahrt, L., 2005. Effect of stability on mixing in open canopies. Agric. For. Meteorol. 135, 169–179.

Li, Z., Miller, D.R., Lin, J.D., 1985. A first-order closure scheme to describe counter-gradient momentum transport in plant canopies. Boundary-Layer Meteorol. 33, 77–83.

Mahrt, L., Lee, X., Black, A., Neumann, H., Staebler, R.M., 2000. Nocturnal mixing in a forest subcanopy. Agric. For. Meteorol. 101, 67–78.

Massman, W.J., 1997. An analytical one-dimensional model of momentum transfer by vegetation of arbitrary structure. Boundary-Layer Meteorol. 83, 407–421.

Massman, W.J., Weil, J.C., 1999. An analytical one-dimensional second-order closure model of turbulence statistics and the Lagrangian time scale within and above plant canopies of arbitrary structure. Boundary-Layer Meteorol. 91, 81–107.

Meyers, T.P., Paw U, K.T., 1986. Testing of a higher-order closure model for modeling airflow within and above plant canopies. Boundary-Layer Meteorol. 37, 297–311.

Meyers, T.P., Paw U, K.T., 1987. Modeling the plant canopy micrometeorology with higher-order closure principles. Agric. For. Meteorol. 41, 143–163.

Monteith, J.L., Unsworth, M., 1990. Principles of Environmental Physics, 2nd ed. Butterworth–Heinemann, Eastbourne, Great Britain, 291 pp.

Oliver, H.R., 1971. Wind profiles in and above a forest canopy. Quart. J. R. Meteorol. Soc. 97, 548–553.

Paw U, K.T., Baldocchi, D.D., Meyers, T.P., Wilson, K.B., 2000. Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. Boundary-Layer Meteorol. 97, 487–511.

Pinker, R.T., Holland, Z.J., 1988. Turbulence structure of a tropical forest. Boundary-Layer Meteorol. 43, 43–63.

Pyles, R.D., Paw U, K.T., Falk, M., 2004. Directional wind shear within an old-growth temperate rainforest: observations and model results. Agric. For. Meteorol. 125, 19–31.

Raupach, M.R., Thom, A.S., 1981. Turbulence in and above plant canopies. Annu. Rev. Fluid Mech. 13, 97–129.

Raupach, M.R., Coppin, P.A., Legg, B.J., 1986. Experiments on scalar dispersion within a model plant canopy. Part I. The turbulence structure. Boundary-Layer Meteorol. 35, 21–52.

Raupach, M.R., Finnigan, J.J., Brunet, Y., 1996. Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy. Boundary-Layer Meteorol. 78, 351–382.

Reifsnyder, W.E., 1955. Wind profiles in a small isolated forest stand. Forest Sci. 1, 289–297.

Schmid, H.P., 2002. Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric. For. Meteorol. 113, 159–184.

Schmid, H.P., Su, H.-B., Vogel, C.S., Curtis, P.S., 2003. Ecosystem-atmosphere exchange of carbon dioxide over a mixed deciduous forest in northern lower Michigan. J. Geophys. Res. 108 (D14), 4417 doi:10.1029/2002JD003011.

Shaw, R.H., 1977. Secondary wind speed maxima inside plant canopies. J. Appl. Meteorol. 16, 514–521.

Shaw, R.H., Pereira, A.R., 1982. Aerodynamic roughness of a plant canopy: a numerical experiment. Agric. Meteorol. 26, 51–65.

Shaw, R.H., den Hartog, G., Neumann, H.H., 1988. Influence of foliage density and thermal stability on profiles of Reynolds stress and turbulence intensity in a deciduous forest. Boundary-Layer Meteorol. 45, 391–409.

Shaw, R.H., Paw U, K.T., Zhang, X.J., Gao, W., den Hartog, G., Neumann, H.H., 1990. Retrieval of turbulent pressure fluctuations at the ground surface beneath a forest. Boundary-Layer Meteorol. 50, 319–338.

Shaw, R.H., Zhang, X.J., 1992. Evidence of pressure-forced turbulent flow in a forest. Boundary-Layer Meteorol. 58, 273–288.

Shaw, R.H., Schumann, U., 1992. Large-eddy simulation of turbulent flow above and within a forest. Boundary-Layer Meteorol. 61, 47–64.

Smith, F.B., Carson, D.J., Oliver, H.R., 1972. Mean wind-direction shear through a forest canopy. Boundary-Layer Meteorol. 3, 178–190.

Su, H.-B., Paw U, K.T., Shaw, R.H., Moeng, C.-H., 1998a. Large-eddy simulation of pressure-gradient-velocity covariance and its parameterization within and above a forest. In: Proceedings of the 23rd Conference of Agricultural For Meteorology. American Meteorological Society, Albuquerque, NM, pp. 229–232.

Su, H.-B., Shaw, R.H., Paw U, K.T., Moeng, C.-H., Sullivan, P.P., 1998b. Turbulent statistics of neutrally stratified flow within and above a sparse forest from large-eddy simulation and field observations. Boundary-Layer Meteorol. 88, 363–397.

Su, H.-B., Shaw, R.H., Paw U, K.T., 2000. Two-point correlation analysis of neutrally stratified flow within and above a forest from large-eddy simulation. Boundary-Layer Meteorol. 94, 423–460.

Su, H.-B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S., Oliphant, A.J., 2004. Spectral characteristics and correction of long-term eddy-covariance measurements over two mixed hardwood forests in non-flat terrain. Boundary-Layer Meteorol. 110, 213–253.

Su, H.-B., Schmid, H.P., Vogel, C.S., Curtis, P.S., 2008. An assessment of observed vertical flux divergence in long-term eddy-covariance measurements over two Midwestern forest ecosystems. Agric. For. Meteorol., doi:10.1016/j.agrformet.2007.08.009.

Thom, A.S., 1971. Momentum absorption by vegetation. Quart. J. R. Meteorol. Soc. 97, 414–428.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean Technol. 14, 512–526.

Villani, M.G., Schmid, H.P., Su, H.-B., Hutton, J.L., Vogel, C.S., 2003. Turbulence statistics measurement in a northern hardwood forest. Boundary-Layer Meteorol. 108, 343–364.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127–150.

Wilson, J.D., 1988. A second-order closure model for flow through vegetation. Boundary-Layer Meteorol. 42, 371–392.

Wilson, N.R., Shaw, R.H., 1977. A higher order closure model for canopy flow. J. Appl. Meteorol. 11, 1197–1205.

Yamada, T., 1982. A numerical model study of turbulent airflow in and above a forest canopy. J. Meteorol. Soc. Jpn. 60, 439–454.