Turbulent eddy motion at the forest-atmosphere interface

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Abstract. Ejection and sweep eddy motions in the atmospheric surface layer (ASL) are widely accepted as being responsible for much of land surface evaporation, sensible heat flux, and momentum flux; however, less is known about this type of eddy motion within the canopy sublayer (CSL) of forested systems. The present study analyzed the ejection-sweep properties at the canopy-atmosphere interface of a 13 m tall, uniformly aged southern loblolly pine stand and a 33 m tall, unevenly aged hardwood stand using velocity and scalar (temperature, water vapor, and carbon dioxide) fluctuation measurements at the canopy-atmosphere interface. It was found that the measured sweeps and ejections time fractions for scalars and momentum are comparable and are in good agreement with other laboratory and field experiments. This investigation demonstrates that the third-order cumulant expansion method (CEM) reproduces the measured relative flux contribution of ejections and sweeps (\(\Delta S_0\)) and the difference between sweep and ejection time fractions for both momentum and scalars at the canopy-atmosphere interface in contrast to findings from a previous ASL experiment. A linkage between \(\Delta S_0\) and the scalar flux budget is derived and tested via the third-order CEM at the canopy-atmosphere interface for the pine and the hardwood stands. It is shown that \(\Delta S_0\) can be related to the dimensionless scalar flux transport term whose gradient is central to the scalar variance budget. Also, the derived relationship is independent of canopy roughness or scalar sources and sinks. Hence this investigation establishes an analytical linkage between second-order closure models, the ejection-sweep cycle, and third-order CEM at the canopy-atmosphere interface. Dissimilarity between the ejection-sweep cycle for scalar and momentum transport is considered via conditional probability distributions at both forest stands. In contrast to a laboratory heat dispersion experiment, it is shown that while the ejection-sweep cycles for scalar and momentum transport are intimately linked, they are not identical. Therefore the results from momentum ejection-sweeps investigations cannot be extrapolated to scalar transport. Comparisons with other laboratory experiments are also discussed, especially in relation to the scalar ejection and sweep time fractions.

1. Introduction

Heat, mass, and momentum transport near rough boundaries by turbulent eddy motions is still a subject of active research in fluid dynamics [see, e.g., Kovasznay et al., 1970, Willmarth, 1975; Townsend, 1976; Raupach et al., 1991], micrometeorology [see, e.g., Kaimal and Finnigan, 1994; Baldocchi, 1989; Amiro, 1990; Shaw et al., 1983], atmospheric chemistry [see, e.g., Guo et al., 1993], and surface hydrology [see, e.g., Brutsaert, 1982; Parlange and Katul, 1995]. For these flow types, downdrafts (or sweeps) and updrafts (or ejections) are recognized as the primary constitutive motions of “coherent” structures responsible for much of the transport; hence interest in the statistical properties of these two types of eddy motions has been pursued through experiments in the laboratory and in the field (see Cantwell [1981], Raupach and Thom [1981], Robinson [1991], Raupach et al. [1991], and Nagano and Tagawa [1995] for reviews). For rough boundary surfaces, the dominant role of downdrafts relative to updrafts in transporting momentum in the near-wall region has been demonstrated through a number of laboratory experiments [e.g., Raupach, 1981], however, less is known about the scalar transport properties of such eddy motion, especially in the roughness sublayer (a region influenced by length scales associated with the roughness elements) of forested systems [see Finnigan, 1985; Raupach, 1988, Wilson, 1989].

Roughness sublayer (RSL), canopy sublayer (CSL), and atmospheric surface layer (ASL) experiments that considered the ejection-sweep relationships for scalar and momentum transport provided results that appear to be inconclusive. Coppin et al.’s [1986] laboratory experiment for a model canopy utilized quadrant analysis of vertical heat flux and showed that sweeps and ejections contribute equally to the heat flux close to the canopy height (h). However, for large heat flux excursions at this height, sweeps were clearly dominant in analogy to momentum. Based on this similarity, Coppin et al. [1986] concluded that heat and momentum transport are similar as long as the scalar source and momentum sink distributions are

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“roughly” coincident. However, other studies did not support these findings. For example, Bergstrom and Hogstrom [1989] showed clear dissimilarity in the ejection-sweep contribution to local, water vapor, and momentum turbulent fluxes from a pine forest. Specifically, the measured ejection contribution to the fluxes of heat and water vapor was larger than the sweep contribution even in the ASL (z/h = 2.36) of their forested system (see Katul et al. [1997a] for a review). Dependence on atmospheric stability conditions was not specifically analyzed in the 1989 Bergstrom and Hogstrom pine experiment [see, e.g., Shaw et al., 1988]. The need to better understand and quantify the relationship between the momentum and scalar ejection-sweep eddy motion within the CSL of forested systems motivated the present investigation.

The objectives of this study are (1) to analyze the statistical properties of the scalar ejection-sweep eddy motions (time fraction and flux contributions) at the canopy-atmosphere interface of forested systems, (2) to evaluate the dissimilarities between the momentum and scalar ejection-sweep eddy motion, and (3) to link the ejection sweep eddy motion to prognostic equations for scalar turbulence closure models (specifically, the flux-transport term) and to test the validity of such closure schemes with field measurements for uniform and non-uniform forested systems. We focus on the ejection-sweep eddy motion close to the forest-atmosphere interface due to the importance of this interface in land-atmosphere interaction investigations.

For the third objective, the third-order cumulant expansion method (CEM), originally used by Frenkiel and Klebanoff [1967, 1973] and Antonia and Atkinson [1973] is utilized. The cumulant expansion method analytically relates departures from Gaussian distributed probability density functions to higher-order cumulants. Linkages between CEM and quadrant analysis, typically used to define ejections and sweeps, have been proposed by Nakagawa and Nacu [1977] and Raupach [1981]. As discussed by Monin and Yaglom [1975, p. 407], the application of CEM approximations for turbulent flows can lead to nonphysical solutions which conflict with the requirement that the spectrum of moments be nonnegative. However, despite the controversial use of CEM in high Reynolds number flows [see, e.g., Brodkey, 1967, pp. 300–301] the third-order CEM is used because of previously established linkages between third-order cumulants, momentum ejections and sweeps, and the turbulent kinetic energy (IKE) transport term discussed by Nakagawa and Nacu [1977] and Raupach [1981]. Also, it is recognized that the measured probability density functions of many turbulent flow variables close to the canopy-atmosphere interface, while non-Gaussian, may still be modeled using CEM approximations [see Baldocchi and Meyers, 1989; Baldocchi, 1989; Amiro, 1990; Amiro and Davis, 1988]. That is, lower-order cumulants of these flow variables can reproduce much of the measured non-Gaussian behavior. However, Chen’s [1990, Figure 14] measurements suggest that third-order CEM predictions of the relative contribution of sweeps and ejections (δS, δS,) to turbulent scalar fluxes underpredicted the eddy correlation measured δS by a factor of 8. Chen [1990] attributed this failure to dissimilarity between momentum and scalar transport. In contrast to Chen [1990], Katul et al. [1997a] recently showed that a third-order CEM reproduced the measured δS, and the scalar probability density functions in the ASL. Additionally, Wyngaard and Sundararajan [1977] reported good agreement between third-order CEM predicted and measured temperature skewness turbulent transport for the convective boundary layer from three separate atmospheric boundary layer (ABL) experiments (see Wyngaard and Sundararajan’s Figure 8). Also, Nagano and Tagawa [1988] showed that a fourth-order CEM reproduced all the third-order scalar and mixed velocity–scalar statistics in both the inner and outer region of turbulent air flow in a heated pipe. This discrepancy in CEM performance for momentum and scalar fluxes motivated us to further investigate third-order CEM approximations to scalar transport, especially at the canopy-atmosphere interface.

In this analysis, 10 Hz velocity (U,) and air temperature (T,) measurements were collected at z = 13 m in a uniform 13 m tall loblolly pine stand and at z = 40 m and z = 33 m above a 33 m tall uneven-aged mixed hardwood stand at the Blackwood division of the Duke Forest near Durham, North Carolina. Water vapor (Q) and carbon dioxide (CO2) concentration measurements were also analyzed to assess the similarity in heat and mass transport by ejections and sweeps at the canopy-atmosphere interface. Except where stated otherwise, the notation used throughout this study is as follows: U(t) = U, U, = U, U, = V, U, = W are the instantaneous longitudinal (U), lateral (V), and vertical (W) velocity components, x1 (x1, x2, x3) are the longitudinal (x), lateral (y), and vertical (z) directions, z is defined from the ground surface, angle brackets indicate time averaging; u, (u, = u, u, = v, u, = w), T, q, co, are the turbulent fluctuations of velocity, air temperature, water vapor, and carbon dioxide concentration about their respective time averages with (u,) = (T,) = (q,) = (co,) = 0 (lowercase variables define turbulent fluctuations about their respective mean values); the z direction is aligned along the mean horizontal wind speed so that (V) = 0.

2. Experimental Setup

Eddy correlation measurements from two forest experiments at the Blackwood Division of the Duke Forest (35°58′N, 79°08′W, elevation of 163 m) near Durham, North Carolina, were used.

2.1. Pine Forest Experiment

The data set used from this site was collected from August to November 1995 over a 6-day period (see Table 1). The site is a uniformly aged 13 m tall loblolly pine forest that extends 1000 m in the north-south direction and 600 m in the east-west direction. The stand was grown from seedlings planted at a 2.4 m by 2.4 m spacing in 1983 following clear cutting and burning. Further details about the understory species, soil type, general climatic conditions, and site description are given by Ellsworth et al. [1995] and Katul et al. [1996, 1997b].

The eddy correlation instruments consisted of a Campbell Scientific Krypton (KOH,O) hygrometer colocated with a three-axis Gill anemometer having a sonic path length d = 15 cm and a gas inlet for a LICOR 6262 CO2/H2O infrared gas analyzer. These instruments were positioned on a 22 m aluminum walkup tower at z/h = 1, where h (z = 13 m) is the canopy height. Other details about the Gill anemometer are given by Katul et al. [1994] and Katul [1994]. The sonic anemometer was positioned at least 70 cm from surrounding leaves to avoid potential sonic wave reflection by the pine needles. The U, V, W, T, Q, and CO2 time series were sampled at 10 Hz and segmented into runs for which the sampling duration per run (T,) was 27.3 min. Hence, 16,384 measurements per flow variable were sampled per run.
The LICOR 6262 infrared gas analyzer was situated on the tower at $z/h = 1.0$ and at 1.5 m from the gas inlet to reduce tubing length. Also, a flow rate of 10 L min$^{-1}$ was used for all eddy-correlation $CO_2$ concentration measurement runs. The $CO_2$ concentration lags due to tube length were computed for each 27.3 min run using the measured cross correlation between the $KH_2O$ and the LICOR 6262 water vapor signals. Further details about the LICOR set up and comparisons with the $KH_2O$ are presented by Kattel et al. [1997b]. The analog signals from all instruments were sampled by a $21 \times$ Campbell Scientific micrologger and transferred to the hard drive of a personal computer via an optically isolated RS232 interface for future processing. The raw data for each run were transformed so that the mean longitudinal velocity $\langle U \rangle$ was aligned along the mean horizontal wind direction and $\langle V \rangle = 0$. Data collection started around 0800 L1 and was terminated about 1800 L1. The amount of data collected each day varied from 17 to 19 runs, as shown in Table 1. The $CO_2$ (and water vapor) from the LICOR 6262 infrared gas analyzer measurements were not available for all runs (see Table 1). Time series were inspected to identify and exclude runs (1) without constant mean temperature and water vapor concentrations, (2) with negative sensible heat flux, and (3) with a cross correlation between the LICOR 6262 and $KH_2O$ water vapor signals less than 0.9. After inspection, 108 runs were used in this CSL investigation for momentum, heat, and water vapor, and 36 runs were available for $CO_2$.

2.2. Hardwood Forest Experiment

This stand is a 33 m tall unevenly aged mature second growth deciduous hardwood mix (oldest individuals exceed 180 years). At this stand, a $40 \text{ m}$ aluminum walkup tower was used to mount eddy correlation instruments. The tower is in an area known as the Meadow Flats, which describes the topography for about 500 m in all directions [Conklin, 1994]. About 1.1 km west-northwest from the tower, the slopes of the Bald Mountains (peak of 232 m) are reached. Similarly, Blackwood Mountain begins its rise (peak of 226 m) about 1.7 km northwest of the tower. The slopes of these hills are less than 15%, and their influence on the air flow close to the tower can be neglected [see Kainal and Finnigan, 1994, p. 169]. The instruments were positioned on the southwest face of the tower to allow unobstructed exposure to the region's prevailing southwest winds. The site details and species composition are presented by Conklin [1994]. For comparison with the pine stand, the normalized leaf area index (LAI) profile for the two stands is shown in Figure 1. Notice that the two stands have very distinct LAI profiles in terms of leaf concentration close to the canopy top. The normalized leaf area index profile for each stand was measured by a LICOR 6000 leaf area index meter. Data sets were collected in 1995 and 1996 and are described below.

2.2.1. The 1995 data set.

In this data set, 10 Hz velocity and temperature measurements were collected using an Applied Technologies, Inc. (ATI) sonic anemometer ($d_{43} = 10$ cm) positioned at $z/h = 1.2$. The measurements were collected for several hours a week from June 25 until September 26, 1995, as part of a biogenic volatile organic compounds (BVOC) emission experiment. The measurements resulted in 45 runs each having a 27.3 min duration (16,384 measurements per flow variable per run).

2.2.2. The 1996 data set.

In this data set, 10 Hz velocity, temperature, and water vapor measurements were collected using the Gill triaxial sonic anemometer and the Campbell Scientific Krypton hygrometer positioned at $z/h = 1.0$. These instruments were moved from the pine forest, positioned at the hardwood forest on June 16, 1996, and operated from June 17.
to July 11, 1996. The experiment was stopped shortly before Hurricane Bertha swept through the region. The system was started at 0900 LT and shut down at 1530 LT or prior to forecasted localized storm events. The logging configuration is identical to that used in the pine forest experiment. The measurements resulted in 93 runs each having a 2/3 min duration (16,384 measurements per flow variable per run).

3. Methods of Analysis

The ejection-sweep cycle for momentum and scalar fluxes is quantified via the conditional sampling methods and quadrant analysis reviewed by Antonia [1981]. Many of these analyzing tools are also described by Katul et al. [1997a]; however, for completeness, a summary of these methods is presented.

3.1. Quadrant Analysis

Quadrant analysis refers to a quadrant decomposition formed from scatter plots of two turbulent quantities such as vertical velocity fluctuations (w) and a fluctuating flow variable (e.g., c = u, T, q, ωz). Four quadrants defined by the Cartesian axes of the scatter plot (S, i = 1, 2, 3, 4) are used to represent four modes of turbulent transport: (1) w > 0 and c > 0, (2) w < 0 and c > 0, (3) w > 0 and c < 0, and (4) w < 0 and c < 0. The quadrant nomenclature for scalar and momentum transport is presented in Figure 2. On the basis of this nomenclature, quadrants 4 and 1 define ejecting motion and quadrants 2 and 3 define sweeping motion for momentum and scalar fluxes (c = T, q), respectively. To facilitate comparison with a wide range of laboratory and field studies, we decided not to apply threshold level approaches for defining the ejections and sweeps (e.g., hyperbolic hole and variable interval time averaging (VITA) approaches described by Willmorth and Lu [1974] and Antonia [1981]; multilevel methods as described by Gao et al. [1992] and Britz and Antonia [1986]; probability density tails threshold described by Katul et al. [1994] or wavelet shrinkage approaches described by Katul and Vidakovic [1996]). To transform the ejection-sweep scalar motions from quadrants 1 and 3 to quadrants 2 and 4, multiply the scalar concentration time series by -1 (for positive fluxes) so that these scalar transport mechanisms coincide with their momentum counterpart (see Figure 2). For CO2, such a transformation is not necessary since the ejections and sweeps coincide with momentum (negative flux).

The stress fraction S2 for quadrant "1" is defined as the flux contribution to $\langle w(t)c(t) \rangle$ from that quadrant:

$$S_2 = \frac{\langle w(t)c(t) \rangle}{\langle wc \rangle}$$

(1)

$$\langle w(t)c(t) \rangle = \frac{1}{T_p} \int_0^{T_p} w(t)c(t)I_i(t) \, dt$$

where double angle brackets are conditional averages over nonzero values and $I_i$ is the indicator function defined by

$$I_i = 1$$

(2a)

if event coordinates $(w, c)$ are within quadrant $i$; $i = 1, 2, 3, 4$ and

$$I_i = 0$$

(2b)

with $S_1 + S_2 + S_3 + S_4 = 1$. While Subramanian et al. [1982] demonstrated that the above approach is ill suited for investigating ensemble structural ejection-sweep geometric elements, they showed that such analysis is reliable for producing conditional averages controlled by ejections and sweeps.

The durations of ejections and sweeps are given by

$$D_i = \frac{1}{T_p} \int_0^{T_p} I_i(t) \, dt$$

(3)

where $D_1$ and $D_4$ are ejection and $D_2$ and $D_3$ are sweep total durations in the sampling period $T_p$ for scalar and momentum transport, respectively. Hence $D_i$ can be viewed as the ratio of the total duration of events in quadrant $i$ to the sampling period $T_p$ and is a measure of the time fraction of events in quadrant $i$ [Coppi et al., 1986]. As discussed by Antonia [1977], $D_{sweep} = D_{sweep}$ for Gaussian-distributed flow variables.

3.2. Cumulant Expansion Method (CEM)

On the basis of a third-order CEM expansion of the joint probability density function $p(\hat{w}, \hat{c})$, given by [see Nakagawa and Nieu, 1977]

$$p(\hat{w}, \hat{c}) = G(\hat{w}, \hat{c}) \left[ 1 + \sum_{j=k=1}^{3} (-1)^{j+k} \frac{Q_{j,k}}{j!k!} \frac{\partial^j \partial^k G(\hat{w}, \hat{c})}{\partial \hat{w}^j \partial \hat{c}^k} \right]$$

(4)

$$G(\hat{w}, \hat{c}) = \frac{1}{2\pi (1 - R_{wc})^{1/2}} \exp \left( -\frac{\hat{w}^2 + 2R_{wc}\hat{w}\hat{c} + \hat{c}^2}{2(1 - R_{wc})} \right)$$

Raupeh [1981] showed that the difference between stress fractions due to sweeps and ejections ($\Delta S_2 = S_4 - S_2$), a measure of the relative importance of the two types of mechanisms, is related to the flow statistics by

$$\Delta S_2 = \frac{R_{wc}}{R_{wc}} \left[ \frac{2C_1}{(1 + R_{wc})^2 + 1 + R_{wc}} \right] + \frac{C_2}{2(1 - R_{wc})}$$

(5a)

$$C_1 = \left( 1 + \frac{R_{wc}}{1 - R_{wc}} \right) \left( M_{03} - M_{02} \right) + \frac{1}{2} \left( M_{21} - M_{12} \right)$$

(5b)
Table 2. Comparison Between the Ejection-Sweep Time Fraction \( D_{\text{eject}} / D_{\text{sweep}} \) for Scalar and Momentum Within and at the Canopy-Atmosphere Interface

<table>
<thead>
<tr>
<th>Flux-Analyzed Surface</th>
<th>Momentum</th>
<th>Heat</th>
<th>Scalar (H₂O/CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_{\text{sweep}} )</td>
<td>( D_{\text{eject}} )</td>
<td>( D_{\text{sweep}} )</td>
</tr>
<tr>
<td>Pine forest ( z/h = 1.0 )</td>
<td>0.31 (0.02)</td>
<td>0.36 (0.03)</td>
<td>0.36 (0.03)</td>
</tr>
<tr>
<td>Hardwood forest ( z/h = 1.2 )</td>
<td>0.30 (0.04)</td>
<td>0.31 (0.04)</td>
<td>0.35 (0.04)</td>
</tr>
<tr>
<td>Hardwood forest ( z/h = 1.0 )</td>
<td>0.31 (0.05)</td>
<td>0.36 (0.03)</td>
<td>0.34 (0.04)</td>
</tr>
<tr>
<td>ASL above grass</td>
<td>0.29 (0.02)</td>
<td>0.30 (0.02)</td>
<td>0.34 (0.02)</td>
</tr>
<tr>
<td>ASL above soil</td>
<td>0.78 (0.07)</td>
<td>0.77 (0.07)</td>
<td>0.77 (0.04)</td>
</tr>
<tr>
<td>ASL above wheat</td>
<td>0.32</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>Smooth heated flat plate</td>
<td>0.30</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td>Smooth flat plate*</td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>Oil open channel</td>
<td>0.28</td>
<td>0.30</td>
<td>...</td>
</tr>
<tr>
<td>Water channel (rough bed)</td>
<td>0.31</td>
<td>0.35</td>
<td>...</td>
</tr>
<tr>
<td>Water channel (smooth bed)</td>
<td>0.31</td>
<td>0.30</td>
<td>...</td>
</tr>
</tbody>
</table>

The values in brackets are for CO₂ and are computed from 36 runs. The smooth heated flat plate data are from Perry and Hoffmann [1976] for \( z/h = 0.3 \). The open channel (water) values are for rough and smooth bed measured at \( z/h = 0.05 \) by Nakagawa and Nieuw [1977]. The open channel (oil) are from Brodkey et al. [1974] for a wall distance \( y^* = (z u_\tau)/v \). The atmospheric surface layer measurements are from Antonia [1977] above a wheat crop \( z/h = 2 \) and Katul et al. [1997a]. The smooth flat plate is from the hydrogen bubble visualization experiments by Kim et al. [1971]. In these visualization experiments the bursting duration \( \sim D_{\text{eject}} / D_{\text{sweep}} \) for \( y^* \) between 5 and 30 is estimated at 0.56 (see Kim et al.’s Figure 13). The numbers in parentheses are the standard deviations about the mean. *\( \frac{D_{\text{eject}}}{D_{\text{sweep}}} = 0.57 \).

\[ C_z = \frac{1}{2} (2 - R_{st}) (M_{gg} - M_{g0}) + \frac{1}{2} (M_{21} - M_{11}) \]  
(5c)

where \( Q_{ij} \) are the cumulants (\( Q_{ij} = 0 \) for \( i + j > 3 \)) in a third-order CEM which can be related to the joint central moments as in the work by Monin and Yaglom [1971]. \( R_{st} \) is the correlation coefficient given by

\[ R_{st} = \langle wc \rangle / \sigma_w \sigma_c \]  
(6)

and \( M_{ij} \) are the dimensionless joint moments given by

\[ M_{ij} = \langle w^i c^j \rangle / (\sigma_w^i \sigma_c^j) \]  
(7)

and \( \sigma_w = \langle w^2 \rangle^{1/2} / \sigma_w \), and \( \sigma_c = \langle c^2 \rangle^{1/2} / \sigma_c \). The \( Q_{ij} \) should not be confused with water vapor concentration \( Q_w \). Notice that \( \Delta S_\delta \), in (5) is a function of third cumulants (or possibly higher for higher CEM expansions as by Nagano and Tagawa [1988]).

Hence a near Gaussian approximation for the joint PDF [see, e.g., Holland, 1967; Antonia and Atkinson, 1973; Antonia, 1977] will not be successful in linking the ejection-sweep cycle to flow statistics (e.g., third cumulants) since \( \Delta S_\delta = 0 \) for such a pdf. In fact, Antonia and Luxton [1974] noted that a fourth-order CEM is necessary to reproduce the flatness factor of the flux.

4. Results and Discussion

We present the results in two subsections. In section 4.1, a comparison between momentum and scalar ejections and sweeps in the CSL is considered via time fractions and joint probability distribution analysis. The second subsection explores the linkages between \( \Delta S_\delta \) and flux budgets at both stands close to the canopy-atmosphere interface using the CEM approach. This height is chosen since it commonly serves as a lower boundary condition for a wide range of phenomenological and numerical models. Validation of the CEM approach for scalar transport close to the canopy atmosphere interface is also discussed.

4.1. CSL Ejection-Sweep Time Fractions

The sweep and ejection durations \( (D_{\text{sweep}}, D_{\text{eject}}) \) for each run were computed; the mean and standard deviations for all runs at the Pine and Hardwood stands are then computed and shown separately in Table 2. We also compared our measured \( D_{\text{sweep}} \) and \( D_{\text{eject}} \) with laboratory and ASL field experiments. From Table 2 it appears that the \( D_{\text{eject}} \) and \( D_{\text{sweep}} \) measured at \( z/h = 1.0 \) (and 1.2) are in good agreement with other experiments for a wide range of surfaces within the roughness sublayer (or the viscous sublayers in the case of smooth surfaces) for both momentum and scalar transport. While it is recognized that the flux contributions of sweeps and ejections are influenced by surface roughness properties [see Raupach, 1981; Shaw et al., 1983], this analysis suggests that the time fraction of ejections and sweeps in both momentum and scalar time series are less sensitive to surface roughness variability close to the canopy-atmosphere interface. This, in part, is due to the large contribution of \( G(\hat{\omega}, \hat{\epsilon}) \) to the magnitudes of \( D_{\text{eject}} \) and \( D_{\text{sweep}} \) irrespective of \( Q_w \), close to the canopy-atmosphere interface as shown above. We consider \( D_{\text{eject}} = D_{\text{sweep}} \) for a Gaussian process for illustration purposes.

Using the joint-Gaussian model of Antonia [1977], \( D_{\text{eject}} \) for scalars is computed by

\[ D_{\text{eject}} = \int_0^\infty d\hat{\epsilon} \int_0^\infty d\hat{\omega} f(\hat{\omega}, \hat{\epsilon}) \]  
(8)

where \( f(\hat{\omega}, \hat{\epsilon}) = G(\hat{\omega}, \hat{\epsilon}) \) defined in (4). Because of the upper limits, we integrated (8) numerically using the "improper integral" routine described by Press et al. [1992, pp. 135–140] and...
Figure 3. The relationship between $D_{\text{eject}}$ computed by numerical integration from a joint Gaussian model (open circles) and $R_{we}$. The regression model (solid line) $D_{\text{eject}} = 1/4 + 1/6R_{we}$ is also shown.

Presented the results in Figure 3. Notice in Figure 3 that when $R_{we}$ varies from $-0.05$ to $-0.5$ which includes all values encountered from a wide range of boundary layer flow experiments, $D_{\text{eject}}$ varies from 0.258 to 0.333.

An approximate linear relationship $D_{\text{eject}} = (1/4 + 1/6|R_{we}|)$ fits the computed $D_{\text{eject}}$ by the Gaussian model quite well (see Figure 3) for the range of $R_{we}$ encountered in boundary layer turbulence (laboratory and field measurements). These computed values are comparable to the values reported in Table 2 in agreement with Antonia’s [1977] conclusions regarding the adequacy of the Gaussian model; nevertheless, the Gaussian model fails to explain the small but persistent differences between $D_{\text{eject}}$ and $D_{\text{sweep}}$ shown in Figures 4a, 4b, and 4c for momentum, heat, and water vapor, respectively. This difference is discussed in section 4.3.3 using a third-order CEM.

It is also interesting to note the similarities in $D_{\text{sweep}}$ and $D_{\text{eject}}$ for momentum and scalars in Table 2. The near equality in the ejection-sweep cycle duration for heat and momentum might suggest some similarity between heat and momentum transport in agreement with Coppin et al. [1986]. The linkages between the two transporting mechanisms through fluid ejections and sweeps are considered next.

4.2. Similarity Between CSL Momentum, Heat, and Water Vapor Ejection-Sweep Cycles

To investigate the similarity between momentum and scalar ejection-sweep cycles in the CSL, we consider a much more stringent measure defined by the conditional probability density matrix $A_{ij}$, given by

$$A_{ij} = P[u_i | c_j] = \frac{P[u_i \cap c_j]}{P[c_j]}$$

(9)

where $P[u_i \cap c_j]$ is the probability that $u$ is in quadrant $i$ and $c_i = T$, $q$, $\Omega_2$ is in quadrant $j$ [see Perry and Hoffmann, 1976] and should not be confused with the index notation. For the purpose of section 4.2, subscripts denote quadrants rather than vectors and the meteorological rather than index notation is used. In (9), the scalar time series is transformed such that $A_{22}$ and $A_{44}$ represent the sweeps and ejection quadrants, respectively. Perry and Hoffmann [1976] measured $A_{ij}$ for a turbulent boundary layer above a smooth flat surface that was maintained at a constant temperature such that the momentum and thermal layers had identical "virtual origins" and the heating was sufficiently small so that buoyancy forces could be,

Figure 4. The variation of measured (symbols) and Gaussian predicted (solid line) $D_{\text{eject}}$ and $D_{\text{sweep}}$ with $R_{we}$ for (a) $c = u$, (b) $c = T$, and (c) $c = q$. 

to a first approximation, neglected. At $z/h = 0.3$, they reported $A_{ij}$ for temperature and velocity to be

$$
A_y = \begin{bmatrix}
0.5 & 0 & 0 & 0.17 \\
0 & 0.77 & 0.38 & 0 \\
0 & 0.27 & 0.63 & 0 \\
0.44 & 0 & 0 & 0.82 \\
\end{bmatrix}
$$

(10)

where $\delta$ is the boundary layer thickness. They also reported that at $z/h = 0.12$, 0.3, and 0.6, $A_{ij}$ did not depart appreciably from the values in (10). Interestingly, Antonia [1977] also measured $A_{22}$ and $A_{44}$ in the ASL above a wheat crop (i.e., $z/h \sim 2$) to be 0.73 and 0.75, respectively which are in good agreement with Perry and Hoffmann [1976]. In Antonia’s [1977] experiment, the wheat crop height ($h$) was 0.7 m and the measurement height ($z$) was 1.48 m. Our measured mean $A_{ij}$ ($c - T$) at $z/h = 1.0$ from all runs for the pine and hardwood stands are

$$
A_y = \begin{bmatrix}
0.45 (0.09) & 0 & 0 & 0.19 (0.06) \\
0 & 0.69 (0.06) & 0.44 (0.11) & 0 \\
0 & 0.31 (0.06) & 0.56 (0.10) & 0 \\
0.55 (0.09) & 0 & 0 & 0.81 (0.06) \\
\end{bmatrix}
$$

(11)

$$
A_y = \begin{bmatrix}
0.41 (0.10) & 0 & 0 & 0.18 (0.05) \\
0 & 0.70 (0.09) & 0.47 (0.12) & 0 \\
0 & 0.30 (0.09) & 0.53 (0.12) & 0 \\
0.56 (0.10) & 0 & 0 & 0.82 (0.05) \\
\end{bmatrix}
$$

(12)

respectively. The numbers in parentheses are the standard deviations about the means. Hence, at the canopy-atmosphere interface, the sweep-ejection cycle for heat and momentum are well coupled and agree with Antonia’s [1977] and Perry and Hoffmann’s [1976] measurements. This coupling is best illustrated by noting that for completely random events, $A_{ij}$ would be

$$
A_y = \begin{bmatrix}
0.50 & 0 & 0 & 0.50 \\
0 & 0.50 & 0.50 & 0 \\
0 & 0.50 & 0.50 & 0 \\
0.50 & 0 & 0 & 0.50 \\
\end{bmatrix}
$$

(13)

However, the ejection-sweep cycle for momentum is not identical to heat transport as evidenced by the departure of $A_{22}$ and $A_{44}$ from unity in (11) and (12). Interestingly, the $A_{ii}$ matrix appears to be independent of roughness as evidenced by comparison between (11) and (12). Therefore close to the canopy-atmosphere interface, momentum and heat transport mechanics are not similar [see also, e.g., McBean, 1974; Raspach, 1979; Thompson, 1979; Bergstrom and Högström, 1989; Chen, 1990] despite the strong coupling between the momentum and heat ejection-sweep cycle. The similarity between heat (active scalar) and water vapor (passive scalar) ejection-sweep cycles remains to be tested.

Several investigators have found that heat and water vapor source nonuniformity are responsible for the departure of $R_{eq}$ from unity [see, e.g., McBean and Miyake, 1972; Warhaft, 1976; Hill, 1989; Padro, 1993; Katul et al., 1995; Roth and Oke, 1995]. In fact, for the present experiment, the measured $R_{eq}$ at $z/h = 1.0$ is not unity and varied from 0.05 to 0.91 as shown in Figure 5 at both sites. It is evident that the source dissimilarity for heat and water vapor (as measured by $R_{eq}$) can potentially produce dissimilar turbulent transport efficiencies (as measured by $R_{eq}$) and ejection-sweep cycles for these scales. Hence we computed $P(u_i \mid q_i)$ and $P(q_i \mid T)$ to further examine the influence of source-sink heat, momentum, and water vapor dissimilarity at the canopy-atmosphere interface on the ejection-sweep cycle. For 108 runs in the pine stand, we obtained

$$
P(u_1 \mid q_1) = \begin{bmatrix}
0.40 (0.07) & 0.67 (0.06) & 0.52 (0.08) & 0.22 (0.06) \\
0 & 0.60 (0.07) & 0.48 (0.08) & 0.78 (0.06) \\
\end{bmatrix}
$$

(14)

$$
P(q_1 \mid T_1) = \begin{bmatrix}
0.58 (0.09) & 0.51 (0.13) & 0.26 (0.11) \\
0 & 0.54 (0.09) & 0.49 (0.13) & 0.74 (0.11) \\
\end{bmatrix}
$$

(15)

Similar findings were also noted at the hardwood forest (e.g., for $P(u \mid q)$, $A_{22} = 0.69 (0.08)$, $A_{44} = 0.82 (0.05)$; for $P(q \mid T)$, $A_{22} = 0.80 (0.11)$, $A_{44} = 0.76 (0.13)$). From the above calculations, it appears that the ejection-sweep relationships between momentum and heat and momentum and water vapor are comparable as evidenced by (14) and (11). However, they are not identical for heat and water vapor transport as shown by the conditional probability calculations in (15). This dissimilarity is due to the fact that temperature is an active scalar [see McBean and Miyake, 1972; Warhaft, 1976; Katul and Par万多, 1994] and that the sources and sinks of heat and water vapor within the canopy, while strongly coupled, are not identical (see Baldocchi [1989] for a review). Interestingly, the measured $P(u_1 \mid (CO_2)_1)$ and $P(u_4 \mid (CO_2)_4)$ for all 36 runs were $0.65 \pm 0.05$ and $0.78 \pm 0.05$, respectively,
which are in good agreement with the water vapor conditional probability measurements and further supports the dissimilarity between momentum and scalar transport close to the canopy-atmosphere interface. For the 36 runs considered, the correlation coefficient between \( q \) and \( \text{CO}_2 \) varied between \(-0.61\) and \(-0.88\).

While the above analysis demonstrates dissimilarities in the statistical properties between momentum and scalar ejection-sweeps, it is not clear whether these departures are responsible for the apparent failure of the third-order CEM for scalar transport as reported by Chen [1990]. Higher-order CEMs may be needed to adequately reproduce the scalar ejection-sweep cycle as demonstrated by Nagano and Tagawa [1988, 1990] for mixed velocity-temperature third moment covariances. Therefore we consider whether the measured \( \Delta S_0 \) for scalar transport can be reproduced from a third-order CEM.

4.3. Third-Order Cumulant Expansion Method Evaluation

This subsection compares third-order CEM predictions and measurements for the two primary variables \( \Delta S_0 \) and \( \alpha = D_{\text{vap}} - D_{\text{eject}} \) traditionally used to quantify the ejection-sweep cycle. Recall that for a Gaussian process \( \Delta S_0 - \alpha = 0 \).

4.3.1. Third-order CEM for predicting \( \Delta S_0 \). In Figures 6a and 6b, the predicted \( \Delta S_0 \) from (5) is compared with the measured \( \Delta S_0 \) obtained from quadrant analysis for scalar and momentum fluxes, respectively, at both sites. Predicted \( \Delta S_0 \) from (5) is in excellent agreement with the measured \( \Delta S_0 \) for momentum, heat, and water vapor contrary to Chen’s [1990] findings but in agreement with the ASL study by Katul et al. [1997a]. As discussed by Katul et al. [1997a], Chen’s [1990] calculations may not have accounted for the fact that the original cumulant discard approximation of Nakagawa and Nezu [1977] is derived for quadrants 2 and 4 and is not appropriate for quadrants 1 and 3 (as evidenced by their sign convention and quadrant definitions). However, for scalar transport (and positive turbulent flux), (5) can still be used if the \( T \) and \( q \) time series are multiplied by \(-1\) as depicted in Figure 2 (see also Katul et al. [1997a] for further discussion). To test the validity of CEM in scalar transport for measures other than \( \Delta S_0 \), we investigate how well this expansion describes the pdf of the individual velocity and scalar time series.

4.3.2. Third-order CEM for predicting pdfs. The third-order CEM used by Nakagawa and Nezu [1977], Räupach [1981], Shaw et al. [1983], and others assumes that the individual probability density function (pdf) of \( w \) and \( c \) can be represented by a third-order Gram-Charlier distribution. The general \( n \)th-order Gram-Charlier distribution of Nakagawa and Nezu [1977] was simplified for third cumulants only to give

\[
p(\hat{c}) = G(\hat{c})\left[1 + \frac{1}{6} Q_3(\hat{c}^3 - 3\hat{c})\right]
\]

\[
G(\hat{c}) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\hat{c}^2}{2}\right)
\]

where \( G(\hat{c}) \) is, as before, the zero-mean unit variance Gaussian distribution and \( Q_3 = (c/\sigma_c)^3 \) is the third cumulant of \( c = [u, w, T, q] \) and is identical to the skewness for the univariate case. For \( u \), it is well recognized that the measured pdf’s do not depart appreciably from \( G(\hat{c}) \) as discussed by Batchelor [1953, pp. 174–175] due to the central limit theorem. For near-neutral and slightly stable ASL flows, Holland [1967], Perry and Hoffmann [1976], Antonia [1977], Thoroddsen and Van Atta [1992], Katul [1994], and Chu et al. [1996] also found that the \( w \) and \( T \) pdf’s do not depart appreciably from \( G(\hat{c}) \). However, for unstable conditions, within the CSL, and close to the wall boundary, departures from Gaussian are well documented for both \( u \) and \( T \) [see, e.g., Maitani and Shaw, 1990; Durst et al., 1987] and higher-order cumulants must be considered. As an illustration, comparisons between measured and third-order CEM predicted pdf’s for \( u, w, T, \) and \( q \) at \( z/h = 1.0 \) (date is August 12, 1995; time is 11:30 L1; pine stand) are shown in Figures 7a, 7b, 7c, and 7d, respectively. Good agreement between measured and third order CEM predicted pdf is noted in Figures 7a to 7d for nearly three decades. Similar findings were also noted for other runs and by others in forested systems (e.g., Baldocchi and Meyers [1988, 1989] and Baldocchi [1989] for momentum transport). A direct consequence of (16) is that the difference between \( D_{\text{eject}} \) and \( D_{\text{sweep}} \) in Figure 4 can be estimated using a third-order CEM and is discussed next.
3.3. Third-order CEM for predicting $\alpha = D_{\text{swEEP}} - D_{\text{eject}}$

It is shown in Figure 4 and Table 2 that while a Gaussian model estimates the correct magnitudes of $D_{\text{eject}}$, this model cannot explain why $D_{\text{eject}} < D_{\text{swEEP}}$. In this section, an approximate relation for the difference between $D_{\text{swEEP}}$ and $D_{\text{eject}}$ is derived using the third-order CEM in analogy to $\Delta S_0$. The fraction of time ($\Gamma$) when $c = u, T, q, CO_2$ is positive (or negative) is, by definition, given by

$$\Gamma_+ = \int_0^\infty P(\xi) d\xi = \frac{6 + \sqrt{2/\pi} Q}{12}$$

$$\Gamma_- = \int_0^\infty P(-\xi) d\xi = \frac{6 - \sqrt{2/\pi} Q}{12}$$

where $P(\ )$ is given by (16). Hence $\alpha = D_{\text{swEEP}} - D_{\text{eject}} = \Gamma_+ - \Gamma_-$. is given by

$$D_{\text{swEEP}} - D_{\text{eject}} = \frac{Q_3}{\sqrt{2\pi}}$$

if the differential time fraction contribution to $\alpha$ from quadrants 2 and 4 is much smaller than the differential contribution from quadrants 1 and 3 for $c = T, q$ (the opposite is true for $c = u, CO_2$). That is, $\alpha \approx (D_3 + D_4) - (D_1 + D_2)$ or $D_3 \approx D_4$ for $c = T, q$. This assumption is generally valid [see, e.g., Chen, 1990; Chu et al., 1996] since the ejection-sweep cycle resides in quadrants 1 and 3 for $c = T, q$, while the $(w, c)$ scatter in quadrants 2 and 4 is approximately symmetric with respect to the origin (the opposite is true for $c = u, CO_2$). In Figure 8, good agreement between measured and predicted $\alpha$ from (18) is noted for both momentum and scalar $(c = T, q)$ transport, respectively. The importance of the skewness factor in the ejection-sweep cycle has been qualitatively well documented by Maitani and Srivastava [1986] and the conclusions of Maitani and Shaw [1990]. However, using the CFM approach, an analytic expression linking the time fraction contribution of the ejection-sweep cycle to skewness can be derived. The analysis in sections 4.2 and 4.3 clearly demonstrates that the third-order CEM is a working approximation for investigating ejections and sweeps in the CS1.

Since the third-order CEM describes $\Delta S_0$ well, we consider whether such an approach can be used to construct closure models in analogy with momentum [see Nakagawa and Nezu, 1977; Raupach, 1981; Nagano and Tagawa, 1988].

4.4. Linkages Between $\Delta S_0$ and Scalar Variance Budgets at the Canopy-Atmosphere Interface

For steady state planar homogeneous turbulence, the scalar variance budget can be written as [Stull, 1988; Garratt, 1992]

$$0 = -2\langle wc \rangle \frac{\partial \langle C \rangle}{\partial z} - 2 \frac{\partial \langle w^2 \rangle}{\partial z} - 2N_{wc}$$

(19)
Figure 8. The variation of $a(t=D_{\text{sheep}} - D_{\text{object}})$ with skewness ($Q_3$) for (a) momentum ($c=\bar{u}$), (b) heat ($c=\bar{T}$), and (c) water vapor ($c=\bar{q}$) at both stands. The solid line is the third-order CEM prediction.

where $N_{wc}$ is the variance dissipation rate. Nakanawa and Nezu [1977], Raupach [1981], and Shaw et al. [1983] showed that the turbulent kinetic energy transport term ($F_{\text{TKE}}$) is related to $\Delta S_0$ using the third-order CEM. In Figure 9, similar relation-

ships between the dimensionless variance transport terms $M_{12} = R_{wc2} = (\bar{w} c^2)/\alpha_2^2\sigma_c$ and the measured $\Delta S_0$ are shown for $z/h = 1.0$ and 1.2 for all scalars ($c = T, q, CO_2$) and at both forest stands. Therefore, to a first approximation, $\Delta S_0$ is strongly related to the dimensionless variance transport term for a wide range of scalar roughness and turbulence conditions.

To evaluate whether $\Delta S_0$ and $R_{wc2} (c = T$ and $q)$ can be derived from CEM as by Katul et al. [1997a], we conducted a sensitivity analysis and we found that setting $M_{30} - M_{02} = 0$ did not influence the performance of (5) as evidenced by the regression results in Table 3. Justification for setting $M_{30} - M_{02}$ to zero is based, in part, on the results from Raupach et al. [1996, Figure 7d] which suggest that both $M_{30}$ and $M_{02}$ are nearly zero close to $z = h$. Raupach et al.’s [1996] arguments are based on the hypothesis that the structure of turbulence close to the canopy-atmosphere interface ($z = h$) resembles a mixing layer with zero velocity skewness. Hence, with this approximation, (5) reduces to

$$\Delta S_0 \approx \frac{1}{2\rho_{wc}} \sqrt{\frac{2\pi}{2\pi}} (M_{21} - M_{12})$$  (20)

(hereafter referred to as the “clipped approximation” as by Katul et al. [1997a]). The term clipped (or truncated) approximation indicates that an incomplete third-order CEM in (20) describes $\Delta S_0$. If a relationship between $M_{12}$ and $M_{21}$ can be derived, then (20) provides an analytic expression between the dimensionless variance transport term and $\Delta S_0$. For guidance to such relationship, we considered Monin and Obukhov [1954] similarity theory (MOST) and the extensive data set of Kader and Yaglom [1990, Figure 5] in the dynamic sublayer (DSL).

On the basis of their DSL measurements (i.e., $(w^2)/u^2 \approx 1.2, (T^2)/u^2 \approx 0.55, \sigma_w/u_\ast = 1.25$, and $\sigma_T/T_\ast = 2.9$, where $u_\ast = (\langle \omega u \rangle)^{1/2}$ and $T_\ast = (\langle w T \rangle)u_\ast$ are the friction velocity and temperature scale, respectively), $M_{12} = M_{21} = 0.11$. Hence, in a first-order analysis, it may still be reasonable to assume that $M_{12} \approx M_{21}$ in the CSL, though the actual magnitudes of these moments may be different than 0.11 as evidenced in Figure 10. Therefore, based on (20) and this order of magnitude estimate, $R_{wc2} - R_{w2c} = 2R_{wc2} - 2R_{wc}(2\pi)^{1/2}\Delta S_0$ (recall in (20) that the $c = T, q$ time series

Figure 9. The variation of the measured dimensionless variance transport term $R_{wc2} (c = T, q, CO_2)$ with $\Delta S_0$. The solid line is derived from the clipped CEM approximation.
Table 3. Sensitivity Analysis and CEM Regression Results for the Pine (P95) and Hardwood (H95, H96) Stands

<table>
<thead>
<tr>
<th>Dependent/Independent</th>
<th>Site</th>
<th>Variable</th>
<th>$z/h$</th>
<th>$n$</th>
<th>$A$</th>
<th>$B$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$T$</td>
<td>1.0</td>
<td>108</td>
<td>0.937</td>
<td>0.021</td>
<td>0.95</td>
<td>0.022</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$T$</td>
<td>1.0</td>
<td>108</td>
<td>1.098</td>
<td>-0.002</td>
<td>0.92</td>
<td>0.033</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>H95</td>
<td>$T$</td>
<td>1.2</td>
<td>45</td>
<td>0.84</td>
<td>0.003</td>
<td>0.98</td>
<td>0.022</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>H95</td>
<td>$T$</td>
<td>1.2</td>
<td>45</td>
<td>0.90</td>
<td>-0.040</td>
<td>0.65</td>
<td>0.036</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>H96</td>
<td>$T$</td>
<td>1.0</td>
<td>93</td>
<td>0.85</td>
<td>0.003</td>
<td>0.99</td>
<td>0.078</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>H96</td>
<td>$T$</td>
<td>1.0</td>
<td>93</td>
<td>0.91</td>
<td>-0.010</td>
<td>0.98</td>
<td>0.034</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$q$</td>
<td>1.0</td>
<td>108</td>
<td>0.87</td>
<td>0.010</td>
<td>0.97</td>
<td>0.013</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$q$</td>
<td>1.0</td>
<td>108</td>
<td>0.96</td>
<td>-0.008</td>
<td>0.94</td>
<td>0.023</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>H95</td>
<td>$q$</td>
<td>1.0</td>
<td>93</td>
<td>0.85</td>
<td>0.008</td>
<td>0.93</td>
<td>0.032</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>H96</td>
<td>$q$</td>
<td>1.0</td>
<td>93</td>
<td>1.01</td>
<td>-0.014</td>
<td>0.90</td>
<td>0.048</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$u$</td>
<td>1.0</td>
<td>108</td>
<td>1.00</td>
<td>0.000</td>
<td>0.96</td>
<td>0.028</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>P95</td>
<td>$u$</td>
<td>1.0</td>
<td>108</td>
<td>1.03</td>
<td>0.043</td>
<td>0.94</td>
<td>0.034</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>H95</td>
<td>$u$</td>
<td>1.2</td>
<td>45</td>
<td>0.92</td>
<td>0.010</td>
<td>0.97</td>
<td>0.046</td>
</tr>
<tr>
<td>$\Delta S_{(Clipped)} / \Delta S_{(EC)}$</td>
<td>H95</td>
<td>$u$</td>
<td>1.2</td>
<td>45</td>
<td>0.94</td>
<td>-0.008</td>
<td>0.97</td>
<td>0.049</td>
</tr>
<tr>
<td>$\Delta S_{(CEM-3)} / \Delta S_{(EC)}$</td>
<td>H96</td>
<td>$u$</td>
<td>1.0</td>
<td>93</td>
<td>0.88</td>
<td>0.014</td>
<td>0.98</td>
<td>0.023</td>
</tr>
</tbody>
</table>

The third order CEM predicted $\Delta S_{(CEM-3)}$ and the clipped $\Delta S_{(Clipped)}$ approximation for scalar and momentum fluxes using equations (5) and (20) are compared to the eddy correlation measured $\Delta S_{(EC)}$. The clipped approximation is derived from (5) by setting $M_{2\theta} = M_{\theta\theta}$ to zero. The regression model is of the form $\Delta S_{(Model)} = A \Delta S_{(EC)} + B$. The number of runs ($n$), coefficient of determinations ($R^2$), and standard error of estimates (SEE) are also shown.

is multiplied by $-1$). Also, with an approximately constant $R_{wz} \approx 0.4$ ($= T, q, CO_2$) determined from MOST, this relationship reduces to $\Delta_S_{wz} = R_{wz}$ and is plotted as a solid line in Figure 9. Given the approximations made above, good agreement between predictions and measurements are noted in Figure 9. This approximation is analogous to the linkage between $F_{KE}$ and $\Delta S_{wz}$ of [Nakagawa and Nezu, 1977; Raupach, 1981, and Shaw et al., 1983] and is much simpler than the models proposed by Nagano and Togawa [1988, 1990, 1995] for the mixed velocity scalar statistics. In fact, the proposed clipped approximation can be used to estimate the relationship between $R_{wz}$ and $\Delta S_{wz}$ measured by Raupach [1981] in a wind tunnel. With $R_{wz} = -R_{w2}$, $R_{wz} = -0.3$ (as from Raupach [1981]), and the clipped approximation $2R_{wz} = \Delta S_{wz}$ results in $R_{w2} = -0.73\Delta S_{wz}$ which is in excellent agreement with the value from Raupach's [1981] data ($R_{w2} = -0.73\Delta S_{wz}$). The good agreement between measured and predicted relationships between $R_{wz}$ and $\Delta S_{wz}$ at both stands along with the best fit to Raupach's data is shown in Figure 11 for illustration purposes.

For scalar transport in the roughness sublayer, $\Delta S_{wz}$ will change dramatically with $z$ as evidenced by a wide range of CSL and RSL experiments [e.g., Bergstrom and Hogstrom, 1989; Shaw et al., 1983; Maitani and Shaw, 1990]; hence our analysis shows that the scalar flux transport is large when large $\Delta S_{wz}$ height variations exist and a balance between production and dissipation in (19) cannot be sustained because of this variation. This imbalance between production and dissipation at $z = h$ is consistent with Raupach et al.'s [1996] mixing layer analogy.

5. Conclusions

This study considered the ejection-sweep eddy motion for momentum and scalar transport in the CSL and the canopy.

![Figure 10](image-url) Figure 10. The relationship between eddy correlation measured $R_{wz}$ and $R_{wz}$ for $c = T, q$, and $CO_2$ at the two stands.

![Figure 11](image-url) Figure 11. Same as Figure 9 but for $c = u$. The solid line is derived from the clipped CEM approximation and Raupach's [1981] wind tunnel measurements.
atmosphere interface of two forest stands for unstable atmospheric conditions. On the basis of our measurements and analysis, the following can be concluded.

1. Close to the canopy-atmosphere interface, the mean durations of the ejection-sweep cycles for scalar (heat, water vapor, and carbon dioxide) and momentum transport are comparable and agree well with a wide range of laboratory experiments carried out above rough and smooth surfaces. Our measurements suggest that the ejection time fraction is well explained by a Gaussian model but not the sweep time fraction. The difference between the sweep and ejection time fractions was analytically derived as a function of skewness using a third order cumulant expansion method and tested at the pine and hardwood stands.

2. At the canopy-atmosphere interface, the ejection-sweep cycle for scalar and momentum are closely coupled but not identical. Therefore analysis of the ejection-sweep cycle for momentum is not sufficient to explain the scalar ejection-sweep eddy motion; and conversely. However, the coupling between the scalar and momentum ejection-sweep cycle is independent of surface roughness for rough surfaces.

3. In contrast to a previous ASL study by Chen [1990], our study demonstrated that the third-order cumulant expansion method (CFM) predicts the individual probability density function for velocity and scalars and the flux contribution of sweeps and ejections to the scalar flux ($\Delta S_0$) well.

4. On the basis of a sensitivity analysis, we showed that simplifications to the $\Delta S_0$, third-order CEM scalar formulation can be efficiently utilized to establish an analytic relationship between $\Delta S_0$ and the mixed velocity scalar third moments. The simplified relation, termed the “clipped approximation,” was used to link $\Delta S_0$ to the scalar variance flux transport term in the scalar variance budget. On the basis of Kader and Yaglom's [1990] data and the clipped approximation, a relationship between $\Delta S_0$ and the dimensionless mixed moment ($\omega c_n)/\sigma^2_{\omega n}$ was proposed and field tested for velocity, temperature, water vapor, and carbon dioxide fluctuations at the canopy-atmosphere interface. It was shown that such relationships can be used to construct closure models if a priori information about the relative importance of ejections to sweeps is available.

5. On the basis of our analysis, it is shown that the usual ASL balance between production and dissipation in the scalar variance budget cannot be sustained in the CSL which is consistent with Raupach et al.'s [1996] mixing layer analogy. We have demonstrated that this imbalance can be explained by the ejection-sweep cycle's contribution (i.e., $\Delta S_0$) to the scalar flux transport term.

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