ESTIMATING CO_2 SOURCE/SINK DISTRIBUTIONS WITHIN A RICE CANOPY USING HIGHER-ORDER CLOSURE MODELS

G. G. KATUL[1,2], R. LEUNING[3], J. KIM[4], O. T. DENMEAD[3], A. MIYATA[5] and Y. HARAZONO[5]

[1]*School of the Environment, Duke University, Durham, NC 27708-0328, U.S.A.;* [2]*Center for Hydrologic Sciences, Duke University, Durham, NC 27708, U.S.A.;* [3]*CSIRO Land and Water, P.O. Box 1666, Canberra, ACT 2601, Australia;* [4]*Department of Atmospheric Sciences, Laboratory for Atmospheric Modeling Research, Seoul, 120-749, Korea;* [5]*National Institute of Agro-Environmental Research, Tsukuba, Ibaraki, 305-8604, Japan*

(Received in final form 7 June 2000)

Abstract. Source/sink strengths and vertical flux distributions of carbon dioxide within and above a rice canopy were modelled using measured mean concentration profiles collected during an international rice experiment in Okayama, Japan (*IREX96*). The model utilizes an Eulerian higher-order closure approach that permits coupling of scalar and momentum transport within vegetation to infer sources and sinks from mean scalar concentration profiles; the so-called 'inverse problem'. To compute the required velocity statistics, a Eulerian second-order closure model was considered. The model well reproduced measured first and second moment velocity statistics inside the canopy. Using these modelled velocity statistics, scalar fluxes within and above the canopy were computed and compared with CO_2 eddy-correlation measurements above the canopy. Good agreement was obtained between model calculations of fluxes at the top of the canopy and measurements. Close to the ground, the model predicted higher respiratory fluxes when the paddy was drained compared to when it was flooded. This is consistent with the floodwater providing a barrier to diffusion of CO_2 from the soil to the atmosphere. The Eulerian sources and flux calculations were also compared to source and flux distributions estimated independently using a Lagrangian Localized Near Field theory, the first study to make such a comparison. Some differences in source distributions were predicted by these analyses. Despite this, the calculated fluxes by the two approaches compared well provided a closure constant, accounting for the influence of 'near-field' sources in the Eulerian flux transport term, was given a value of 1.5 instead of the value of 8 found in laboratory studies.

Keywords: Canopy turbulence, CO_2 sources and sinks, Higher-order closure models, Inverse models.

1. Introduction

The partitioning of sources* and sinks of scalar entities such as carbon dioxide (CO_2) and water vapour within the canopy volume and between vegetation and soils continues to be a fundamental and practical research problem in micrometeorology and plant ecology (Leuning et al., 2000). One approach to investigate such partitioning is to utilize functional relationships between turbulent fluxes and

* Sources will be used to cover sinks as well in the rest of the paper.

Boundary-Layer Meteorology **98:** 103–125, 2001.

mean scalar concentration gradient measurements within the canopy. Historically, research effort was devoted to deriving such functional relationships by linking local turbulent fluxes to mean local concentration gradient via an effective turbulent diffusivity (*K-Theory*). Over the past 30 years, theoretical considerations and experiments have demonstrated that scalar and momentum fluxes within many canopies do not obey *K-Theory* (Deardorff, 1972, 1978; Corrsin, 1974; Shaw, 1977; Sreenivasan et al., 1982; Denmead and Bradley, 1985; Finnigan, 1985; Raupach, 1988; Wilson, 1989). To alleviate such limitations, both Lagrangian and higher-order Eulerian closure approaches have been developed to estimate source distributions from measured mean concentration gradients.

Raupach (1988, 1989a,b) proposed the 'Localized Near Field' (*LNF*) theory of dispersion in plant canopies, which showed that the scalar concentration profile within the canopy is the result of contributions from both local and distant sources. The *LNF* theory assumes that the canopy is horizontally homogeneous at each height so that net transport is only in the vertical direction; that near-field transport can be described as if it occurred in a Gaussian homogeneous turbulent flow characterized by a standard deviation in vertical velocity $\sigma_w(z)$ and a Lagrangian time scale $\tau_L(z)$; and that the contribution to the concentration field from distant (far-field) sources is strictly diffusive. With these assumptions, expressions between source strength and mean concentration profile can be derived and solved. Explicit accounting of near field effects explained the non-local relationship between turbulent fluxes and mean concentration gradients (Raupach, 1988; Kaimal and Finnigan, 1994; Katul et al., 1997a). The *LNF* approach was used by a number of authors (Raupach et al., 1992; Denmead and Raupach, 1993; Denmead, 1995; Katul et al., 1997a; Massman and Weil, 1999; Leuning et al., 2000; Leuning, 2000) with good agreement reported between modelled turbulent fluxes and those measured above the canopy. Lagrangian approaches cannot predict the velocity field needed to drive such scalar transport calculations, and hence the velocity statistics must be specified a priori in the *LNF* framework. It is important to recognize that Lagrangian approaches such as *LNF* require specification of the integral Lagrangian time scale as a function of height, but in practice such statistics are not explicitly measured and must be inferred from their Eulerian counterparts. The *LNF* theory also requires vertical profiles of $\sigma_w(z)$ but these can also be inferred from their Eulearian counterpart when the flow inhomogeneity is not large.

Recently, Katul and Albertson (1999) developed an Eulerian theory that couples momentum and scalar transfer within vegetation using second-order closure principles. Their approach resulted in expressions relating scalar turbulent flux profiles to mean scalar concentration gradients. Additionally, such an approach permits estimation of needed velocity statistics as part of their scalar transport calculations if the leaf area density and the drag properties of the foliage are known or specified. The necessary scalar measurements for both *LNF* and the approach in Katul and Albertson (1999) are identical; yet the simplifying approximations in their formulations are markedly different. Hence, given the uncertainty (and perhaps non-uniqueness) in inferring scalar sources and sinks from measured mean concentration profiles (the 'inverse problem'), it is necessary to investigate a spectrum of methods that differ in basic principles, approximations, and parameterization schemes. Agreement between such methods adds necessary confidence in computed sources from such inverse calculations.

The objective of this study is to investigate the inverse method developed by Katul and Albertson (1999) for the rice canopy measurements of *IREX96* (the 1996 International Rice Experiment) in Okayama, Japan, for both velocity statistics and scalar fluxes. In this experiment, detailed velocity statistics and mean scalar concentration profiles were measured within and above the canopy for a sequence of 7 days. Additionally, time-matching scalar fluxes were measured above the canopy. A unique feature about *IREX96* was the alternation of flooding and drainage of the rice paddy, which significantly altered both soil respiration and CO_2 uptake by the rice canopy resulting from the presence or absence of the diffusion barrier to CO_2 caused by the floodwater. Comparisons with *LNF* source calculations reported by Leuning et al. (2000) and Leuning (2000) are also discussed.

2. Theory

Velocity statistics must be known to estimate scalar sources and fluxes within and above the canopy from measurements of mean concentration profiles, and here we use a second-order closure model to estimate the required velocity statistics. While third-order momentum transport closure schemes have been developed for canopy flows (Meyers and Paw U, 1986; Meyers and Baldocchi, 1991), a recent study by Katul and Albertson (1998) concluded that second-order closure models perform 'no worse' than third-order schemes, and thus we have used a computationally simple second-order closure model proposed by Wilson and Shaw (1977, WS77 hereafter). This model, briefly described below, has been tested for a wide range of vegetation types including forests (e.g., Katul and Albertson, 1998; Katul and Chang, 1999) with good agreement between measured and modeled σ_w.

2.1. Momentum transport (WS77)

Upon time and horizontally averaging the mean momentum and Reynolds stress equations for neutral conditions, the second-order closure model of WS77 reduces to

$$
\begin{aligned}
0 &= -\frac{\mathrm{d}\langle\overline{u'w'}\rangle}{\mathrm{d}z} - C_d a(z)\langle\bar{u}\rangle^2 \\
0 &= -\langle\overline{w'^2}\rangle\frac{\mathrm{d}\langle\bar{u}\rangle}{\mathrm{d}z} + 2\frac{d}{\mathrm{d}z}\left(q\lambda_1\frac{\mathrm{d}\langle\overline{u'w'}\rangle}{\mathrm{d}z}\right) - \frac{q\langle\overline{u'w'}\rangle}{3\lambda_2} + C_w q^2\frac{\mathrm{d}\langle\bar{u}\rangle}{\mathrm{d}z}
\end{aligned}
$$

$$
\begin{aligned}
0 &= -2\langle\overline{u'w'}\rangle\frac{\mathrm{d}\langle\bar{u}\rangle}{\mathrm{d}z} + \frac{\mathrm{d}}{\mathrm{d}z}\left(q\lambda_1\frac{\mathrm{d}\langle\overline{u'^2}\rangle}{\mathrm{d}z}\right) + 2C_d a(z)\langle\bar{u}\rangle^3 \\
&\quad -\frac{q}{3\lambda_2}\left(\langle\overline{u'^2}\rangle - \frac{q^2}{3}\right) - \frac{2}{3}\frac{q^3}{\lambda_3} \\
0 &= \frac{d}{\mathrm{d}z}\left(q\lambda_1\frac{\mathrm{d}\langle\overline{v'^2}\rangle}{\mathrm{d}z}\right) - \frac{q}{3\lambda_2}\left(\langle\overline{v'^2}\rangle - \frac{q^2}{3}\right) - \frac{2}{3}\frac{q^3}{\lambda_3} \\
0 &= \frac{\mathrm{d}}{\mathrm{d}z}\left(3q\lambda_1\frac{\mathrm{d}\langle\overline{w'^2}\rangle}{\mathrm{d}z}\right) - \frac{q}{3\lambda_2}\left(\langle\overline{w'^2}\rangle - \frac{q^2}{3}\right) - \frac{2}{3}\frac{q^3}{\lambda_3}.
\end{aligned}
\tag{1}
$$

In Equation (1), u_i ($u_1 = u$, $u_2 = v$, $u_3 = w$) are the instantaneous velocity components along x_i, x_i ($x_1 = x$, $x_2 = y$, $x_3 = z$) are the longitudinal, lateral, and vertical directions, respectively, $(\bar{.})$ and $\langle . \rangle$ denote time and horizontal averaging operators respectively (Raupach and Thom, 1981; Raupach and Shaw, 1982; Raupach et al., 1991), primes denote departures from the temporal averaging operator, $q = \sqrt{\langle\overline{u_i'u_i'}\rangle}$ is a characteristic turbulent velocity, λ_1, λ_2, and λ_3 are characteristic length scales for the triple-velocity correlation, the pressure-velocity gradient correlation, and viscous dissipation, respectively, C_w is a constant, k (= 0.4) is Von Karman's constant, C_d is the foliage drag coefficient, $a(z)$ is the leaf area density, and a_1, a_2, a_3, and C_w are closure constants that can be determined such that the flow conditions well above the canopy reproduce established surface layer similarity relations (see Appendix A). The numerical values of these constants are tabulated in Table I and are determined from measurements and similarity relations as discussed in Katul and Albertson (1999). The characteristic length scales are defined by

$$
\begin{aligned}
&\lambda_j = a_j L(z); \quad j = 1, 2, 3 \\
&L(z_i) = \min\begin{cases} L(z_{i-1}) + k\,\mathrm{d}z \\ \frac{\alpha}{C_d a(z_i)} \end{cases} \\
&L(0) = 0,
\end{aligned}
$$

where α is an empirical constant and $\mathrm{d}z = z_i - z_{i-1}$. With estimates of these five constants (a_1, a_2, a_3, C_w, and α), the five ordinary differential equations in (1) can be solved for the five flow variables $\langle\bar{u}\rangle$, $\langle\overline{u'w'}\rangle$, $\langle\overline{u'^2}\rangle$, $\langle\overline{v'^2}\rangle$, and $\langle\overline{w'^2}\rangle$ if appropriate boundary conditions are specified. These equations were derived by assuming (1) steady-state adiabatic flow, (2) the pressure form drag can be represented by a drag force, (3) the viscous drag is negligible relative to the form drag, (4) all the triple-velocity products are closed by a gradient–diffusion approximation (Donaldson, 1973; Mellor, 1973; Mellor and Yamada, 1974; WS77; Shaw, 1977; Andren, 1990; Canuto et al., 1994; Abdella and McFarlane, 1997), (5) the pressure-velocity

TABLE I

The WS77 closure constants used in modeling the velocity statistics of the *IREX96* experiment.

Constant	Value	Comment
a_1	0.262	Determined by matching the momentum second-order closure model
a_2	3.65	with commonly used ASL values for $A_u = 2.7$, $A_v = 2.4$, and $A_w = 1.25$.
a_3	32.23	The Atmospheric Surface Layer (ASL) similarity values are from
C_w	0.083	Panofsky and Dutton (1984) for neutral atmospheric flows and are assumed to exist at $z/h = 3.3$. These constants are dependent on the assumed A_u, A_v, and A_w.
α	0.014	Determined by us to ensure that both $\langle\overline{u'w'}\rangle = 0$ and
C_d	0.3	$\frac{\mathrm{d}\langle\overline{u'w'}\rangle}{\mathrm{d}z} = 0$ at $z/h = 0$ and that $\frac{\mathrm{d}\langle\bar{u}\rangle}{\mathrm{d}z} = \frac{u_*}{k(z-d)}$ at $z/h = 3.3$. These values can vary with vegetation types.
C_4	3	See Appendix A.
C_8	8.0 (1.5[a])	From Andre et al. (1979).

[a]Used in sensitivity analysis. This value best matches *LNF*.

gradients can be represented using return-to-isotropy principles, (6) the viscous dissipation is isotropic and dependent on the local turbulence intensity (Mellor, 1973), and neglecting all horizontal gradients.

The main criticism of the WS77 model is the arbitrary choice of the empirical length scale $L(z)$. To avoid this, Wilson (1988) proposed an alternate closure scheme based on the formulation of Hanjalic and Launder (1972), Reynolds and Cebeci (1976), and Gibson and Launder (1978), which use a relaxation time scale that depends on the ratio of turbulent kinetic energy and mean dissipation rate (hereafter referred to as W88). The W88 model follows the traditional closure framework for bounded and free shear flow (Gibson and Launder, 1978) modified to include the drag effects of the canopy. Katul and Chang (1999) compared the flow statistics computed using the models of WS77 and W88 against measurements in a pine forest and found that the performance of these two models to be very comparable. Hence, in this study, we utilize the simpler WS77 approach for computing the flow statistics needed to drive the scalar transport calculations.

2.2. Scalar Transport: Second-Order Closure Model

With time and horizontal averaging, the scalar continuity and turbulent vertical flux equations reduce to (Lewellen et al., 1980; Finnigan, 1985; Meyers and Paw U, 1987; Raupach, 1988; Wilson, 1989)

$$\frac{\partial\langle\bar{c}\rangle}{\partial t} = 0 = -\frac{\partial\langle\overline{w'c'}\rangle}{\partial z} + S_c \tag{2}$$

$$\frac{\partial\langle\overline{w'c'}\rangle}{\partial t} = 0 = -\langle\overline{w'^2}\rangle\frac{\partial\langle\bar{c}\rangle}{\partial z} - \frac{\partial\langle\overline{w'w'c'}\rangle}{\partial z} - \left\langle\overline{c'\frac{\partial p'}{\partial z}}\right\rangle, \tag{3}$$

where S_c is the scalar source (or sink) term due to mass release (or uptake) by the ensemble of leaves within the averaging volume. By neglecting the scalar drag and waving source production terms in Equation (3), no new terms are introduced by the horizontal-averaging operation.

Closure Approximations

The closure approximation we used for the scalar flux transport term in Equation (3) is given by (Meyers and Paw U, 1987; André et al., 1979)

$$\langle\overline{w'w'c'}\rangle = \frac{\tau}{C_8}\left[-\langle\overline{w'^3}\rangle\frac{\partial\langle\bar{c}\rangle}{\partial z} - \langle\overline{w'c'}\rangle\frac{\partial\langle\overline{w'^2}\rangle}{\partial z} - 2\langle\overline{w'^2}\rangle\frac{\partial\langle\overline{w'c'}\rangle}{\partial z}\right], \tag{4}$$

where C_8 is a closure constant and the time scale $\tau = q^2/\langle\epsilon\rangle$ is a relaxation time scale that varies with height, and $\langle\epsilon\rangle$ is the mean turbulent kinetic energy dissipation rate ($= 2q^3/\lambda_3$ in the WS77 model). The above formulation for $\langle\overline{w'w'c'}\rangle$ is more general than the gradient diffusion formulation proposed by Wilson (1989) since gradients in $\langle\overline{w'c'}\rangle$ and $\langle\overline{w'w'}\rangle$ both influence the transport of turbulent flux. However, this formulation still suffers from traditional weaknesses of flux-gradient closure (Deardorff, 1972, 1978) and fails to capture the statistical properties of the ejection-sweep cycle (Katul et al., 1997b).

The pressure gradient-scalar covariance in Equation (3) is modelled after Finnigan (1985), but without the waving-source production term, and is given by:

$$\left\langle\overline{c'\frac{\partial p'}{\partial z}}\right\rangle = C_4\frac{\langle\overline{w'c'}\rangle}{\tau}, \tag{5}$$

where C_4 is another closure constant. To compute the flux-profile from the mean scalar concentration profile, Equations (4) and (5) are combined with Equation (3) and re-written as:

$$A_1(z)\frac{\partial^2\langle\overline{w'c'}\rangle}{\partial z^2} + A_2(z)\frac{\partial\langle\overline{w'c'}\rangle}{\partial z} + A_3(z)\langle\overline{w'c'}\rangle = A_4(z), \tag{6}$$

where

$$A_1(z) = \frac{2\tau}{C_8}\langle\overline{w'w'}\rangle$$

$$A_2(z) = \frac{\tau}{C_8}\frac{\partial\langle\overline{w'w'}\rangle}{\partial z} + 2\frac{\partial}{\partial z}\left(\frac{\tau}{C_8}\langle\overline{w'w'}\rangle\right)$$

$$A_3(z) = \frac{\partial}{\partial z}\left(\frac{\tau}{C_8}\frac{\partial\langle\overline{w'w'}\rangle}{\partial z}\right) - C_4\frac{1}{\tau}$$

$$A_4(z) = \langle\overline{w'w'}\rangle\frac{\partial\langle\bar{c}\rangle}{\partial z} - \frac{\partial}{\partial z}\left(\frac{\tau}{C_8}\langle\overline{w'w'w'}\rangle\right)\frac{\partial\langle\bar{c}\rangle}{\partial z} - \left(\frac{\tau}{C_8}\langle\overline{w'w'w'}\rangle\right)\frac{\partial^2\langle\bar{c}\rangle}{\partial z^2}.$$

The velocity statistics relevant to scalar transport (e.g., $\langle\overline{w'w'}\rangle$ and $\langle\overline{w'w'w'}\rangle$) as well as the relaxation time scale (τ) are all computed using the second-order closure models for momentum transport. Note that the coefficients $A_1(z)$, $A_2(z)$, and $A_3(z)$ are dependent only on the profiles of the velocity statistics. The mean scalar concentration profile is directly measured and is used to compute $A_4(z)$. Equation (6) can be solved for $\langle\overline{w'c'}\rangle$, which upon differentiation with respect to z provides the source profile (S_c) as in Equation (2). Since the CO_2 flux from the soil is commonly large and not known *a priori*, a reasonable boundary condition is a near-constant flux with height at $z = 0$. Hence, the boundary conditions for scalar fluxes in Equation (6) are:

$$z \gg h: \quad \langle\overline{w'c'}\rangle = -k(z-d)u_*\frac{\mathrm{d}\langle\bar{C}\rangle}{\mathrm{d}z}$$

$$z = 0: \quad \frac{\mathrm{d}\langle\overline{w'c'}\rangle}{\mathrm{d}z} = 0, \tag{7}$$

where d, the zero-plane displacement, was estimated from the 'centre of pressure' method as in Thom (1971) and Shaw and Pereira (1982) using:

$$d = \frac{\int_0^h z\frac{\partial\langle\overline{u'w'}\rangle}{\partial z}\mathrm{d}z}{\int_0^h \frac{\partial\langle\overline{u'w'}\rangle}{\partial z}\mathrm{d}z}.$$

For $z/h > 1$, $\langle\overline{w'c'}\rangle$ is assumed constant and identical to its value at $z/h = 1$ to satisfy Equation (2) when $S_c = 0$. Details of the methods used to solve the coupled second-order closure scheme for momentum and for scalar transport (Equations (6) and (7)) are discussed in Katul and Albertson (1999).

3. Experiment

The experimental setup was described in Leuning et al. (2000) but is reviewed here briefly for completeness. The measurements were made within and above a spatially uniform rice paddy, 0.72 m (= h) tall, located at the agricultural station of Okayama University (Japan) from 6–13 August 1996 as part of an International Rice Experiment (*IREX96*). The field was 300 m by 300 m and was surrounded by similar rice fields in all directions. The field was drained from 6 August until midday 9 August when it was flooded to a depth of 0.08–0.1 m in accordance with local agricultural practices. The leaf area density was measured by a canopy analyzer (LAI-2000 LiCor Inc., Lincoln Nebraska) and the leaf area index (*LAI*) was 3.1 ($\pm 0.3_{std}$).

The mean CO_2 concentrations were measured at 0.12, 0.24, 0.36, 0.48, 0.60, 0.72, 1.1, and 2.4 m above the ground (or water surfaces) using a gas-sampling system and a non-dispersive infrared gas analyzer (LI-6251, LiCor, Lincoln, Nebraska). A miniature three-dimensional sonic anemometer with a 50 mm path length (Kaijo Denki, DAT 395, Tokyo, Japan) was positioned at various levels (z/h = 0.35, 0.45, 0.55, 0.63, 0.77, 0.83, 0.90, 1.05) to measure velocity statistics inside and near the canopy top. An additional triaxial sonic anemometer (Solent 1021 R, Gill Instruments, Lymington, U.K.) with a path length of 0.15 m was installed at z/h = 3.3 to measure the velocity statistics well above the canopy. Measurements from the two sonic anemometers were combined to construct an ensemble of normalized turbulent statistics at each level occupied by the miniature sonic anemometer.

Co-located with the Gill sonic anemometer was an open path infrared gas analyzer (E009, Advanet Inc., Okayama, Japan) to measure the CO_2 fluxes above the canopy using the eddy covariance technique. The sampling duration for the profiling and eddy-covariance systems was 30 minutes. The experiment resulted in 270 half-hour runs during which the profiling and eddy-covariance systems functioned simultaneously. All calibrations, corrections, measurement conditioning and post-processing are discussed in Leuning et al. (2000).

4. Results and Discussion

An assessment of the ability of the models to reproduce measured velocity statistics, scalar fluxes, and known biophysical properties is considered next. Comparison with *LNF* CO_2 flux and source calculations reported by Leuning et al. (2000) and Leuning (2000) are presented.

4.1. Modelling the Velocity Field

Figure 1 shows the modelled and measured $\langle \bar{u} \rangle / \langle \overline{u_R} \rangle$, $\langle \overline{u'w'} \rangle / u_*^2$, σ_w / u_*, σ_u / u_8, and the skewness of $w (Sk_w)$ as a function of normalized height (z/h), where u_R and u_* are the horizontal windspeed and friction velocity measured at the reference height of 2.2 m. The measured normalized leaf area density $(a(z)h)$ is also shown. Detailed comparisons in Figure 1 and Table II between velocity statistics predicted

TABLE II

Comparison between overall measured and modelled flow variables for WS77. The statistics for the regression model $y = Ax + B$ are presented where y are measured and x are modelled flow statistics. The coefficient of determination (R^2) and the standard error of estimate (SEE) are also tabulated along with the root-mean-squared error (RMSE).

Variable	R^2	SEE	Slope A	Intercept B	RMSE
$\frac{\langle \bar{u} \rangle}{\langle u_R \rangle}$	0.97	0.05	1.01	−0.02	0.05
$\frac{\langle \overline{u'w'} \rangle}{u_*^2}$	0.60	0.26	0.83	−0.15	0.26
$\frac{\sigma_u}{u_*}$	0.65	0.51	1.10	−0.32	0.50
$\frac{\sigma_w}{u_*}$	0.84	0.14	1.21	−0.06	0.15
$\frac{\overline{w'w'w'}}{u_*^3}$	0.02	0.10	0.04	−1.10	0.67

by WS77 and measurements showed that the model reasonably reproduced the first and second moments of the flow (i.e., $\langle \bar{u} \rangle$, $\langle \overline{u'w'} \rangle$ and σ_u and σ_w). As expected, agreement between measured and modelled Sk_w is poor indicating that a gradient-diffusion closure

$$\langle \overline{w'w'w'} \rangle = -3q\lambda_1 \frac{\mathrm{d}\langle \overline{w'w'} \rangle}{\mathrm{d}z},$$

is inadequate inside such canopies. However, what must be emphasized is that while the modelled Sk_w does not compare well with measurements, modelled first and second moments inside the canopy are satisfactory (see Katul and Albertson, 1998). Since $\overline{w'w'w'}$ is needed in estimating scalar sources, the poor performance of WS77 may be problematic for scalar transport. Sensitivity analysis reported in Katul and Albertson (1999) suggest that the parameterization of σ_w is much more critical than Sk_w. In fact, Katul and Albertson (1999) found that the scalar fluxes changed by less than 5% when the calculations were repeated with a constant $Sk_w(z) = 0$.

4.2. Comparisons between Eulerian and LNF sources and fluxes

Figure 2 compares the Eulerian modelled CO_2 fluxes with a modified Lagrangian *LNF* theory that incorporates atmospheric stability corrections on the vertical profiles of the Lagrangian time scale and vertical velocity variance (Leuning et al., 2000; Leuning, 2000). The σ_w profile used in the Leuning *LNF* analysis is shown in Figure 1 (dashed line). In the *LNF* calculations, the source strengths were estimated for five canopy layers, each of thickness Δz = 0.144 m via the regression

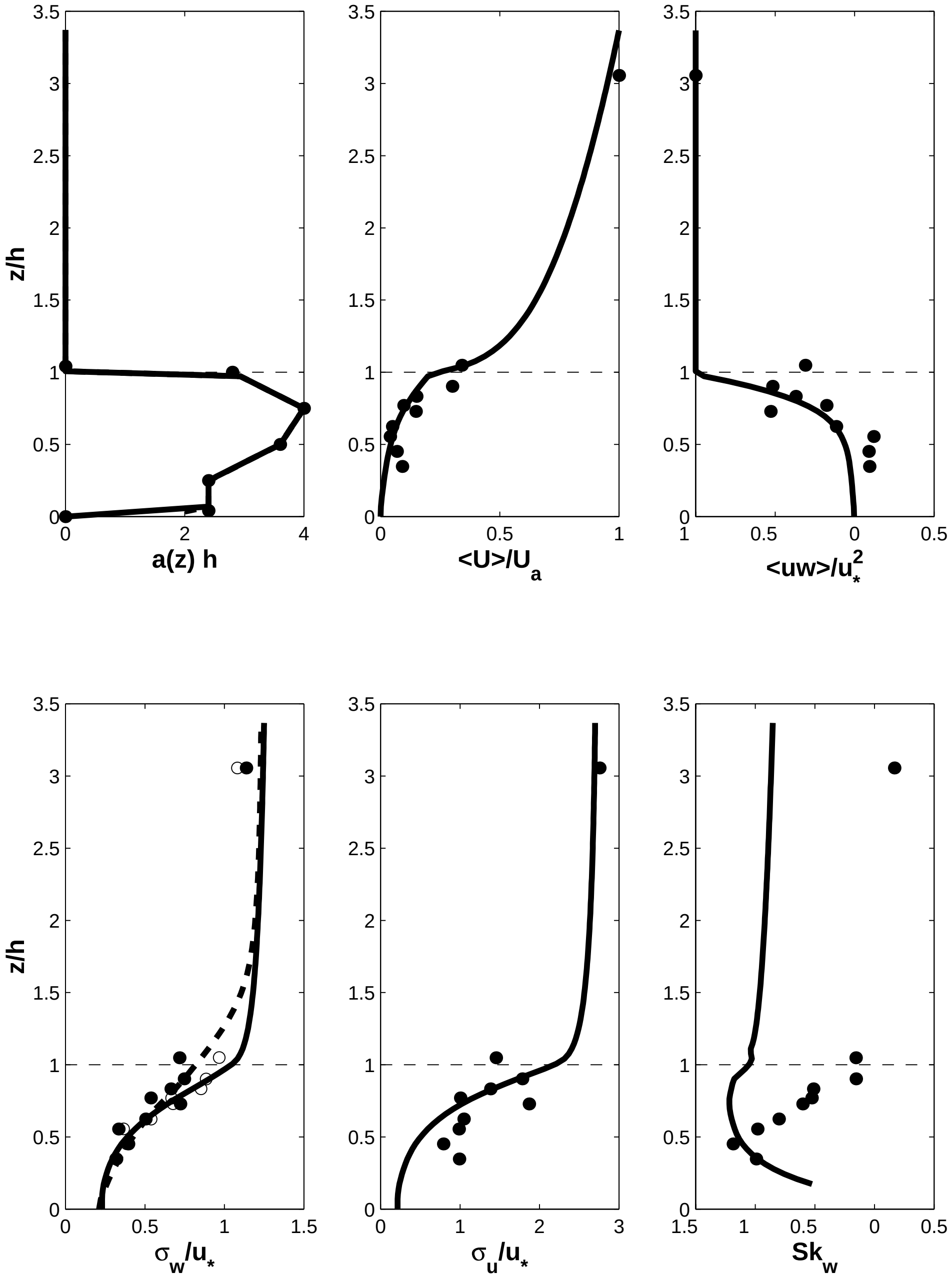

Figure 1. Comparison between overall ensemble-averaged measured (closed circles) and modelled normalized velocity statistics by the WS77 (solid line) closure model. The overall ensemble includes near neutral, unstable, and stable atmospheric surface layer stability runs. The normalized measured leaf area density is also shown. Normalizing variables are the friction velocity at the canopy top (u_*) and the canopy height (h). The near-neutral σ_w/u_* runs are shown separately for clarity (open circles). The dotted line in σ_w/u_* is used by Leuning et al. (2000) for the Localized Near Field Theory calculations.

algorithm described in Raupach (1989). Using the computed *LNF* sources, the *LNF* fluxes were calculated via Equation (2). Both analyses gave similar results for the lowest layers ($z/h = 0.2$, and 0.4). In particular, both methods predicted larger CO_2 fluxes when the field was drained. The larger CO_2 fluxes for the drained field conditions, when compared to flood conditions, are consistent with the conclusions of Miyata et al. (2000). In essence, the standing water acts as a diffusive barrier to CO_2 exchange from the soil surface to the atmosphere. However, for the middle and upper canopy layers ($z/h = 0.6$ and 0.8), the Eulerian approach underestimated daytime fluxes by a factor of 2 relative to the estimates using *LNF* theory. This flux underestimation by the Eulerian model was further confirmed by a multi-layer model of canopy physiology described in Leuning (2000) (not shown here). Such underestimation by the Eulerian model motivated us to re-consider the magnitude of the flux-transport term in Equation (3).

The closure parameter C_8 in the Eulerian analysis is the only parameter that cannot be estimated *a priori* by asymptotic matching to well-established atmospheric surface-layer similarity relationships. Careful examination of Equation (4) demonstrates that a reduction in C_8 determines the magnitude of $\langle\overline{w'w'c'}\rangle$ and thereby the relative contribution of the flux-transport term to the shear production term as evidenced by Equation (3). Recall also that $\langle\overline{w'w'c'}\rangle$ is the main contributor to 'counter gradient' flow inside the vegetation. A value of $C_8 = 8$ as originally proposed by Andre et al. (1979) was used to produce the results of Figure 2. To examine whether the systematic departures between the *LNF* and Eulerian approaches are dependent on C_8, we reduced C_8 to 1.5 and found that discrepancies between the two inverse models was reduced by about 35% as evidenced by Figure 3 and the regression slopes in Table III.

It must be emphasized that $C_8 = 8$ was not originally derived for canopy flow but was estimated by Andre et al. (1979) after optimizing their closure model of temperature variance calculations to match the penetrative convection measurements of Willis and Deardorff (1974) and the asymmetric channel-flow experiments of Hanjalic and Launder (1972). Hence, there is no clear theoretical rationale for assuming that C_8 from such experiments can be transferred, with no alterations, to canopy flow. Despite obtaining better agreement between the *LNF* and Eulerian approaches with the smaller value of C_8, differences in the details of predicted source distributions still exist as shown in Figure 4, particularly in the top canopy layers ($z/h = 0.6$ and 0.8).

To further highlight the nature of these differences, the source and flux distributions at noon within the canopy for 8 August (dry conditions) and 11 August (flooded conditions) are shown in Figure 5. It is clear that the Eulerian and *LNF* inverse analyses drastically differed in their predictions of CO_2 *source distributions* within a rice canopy despite reasonable agreement in the flux profiles. The second-order closure model indicated an approximate bimodal daytime sink distribution, with maxima in the top and bottom thirds of the canopy. In contrast, the *LNF* ana-

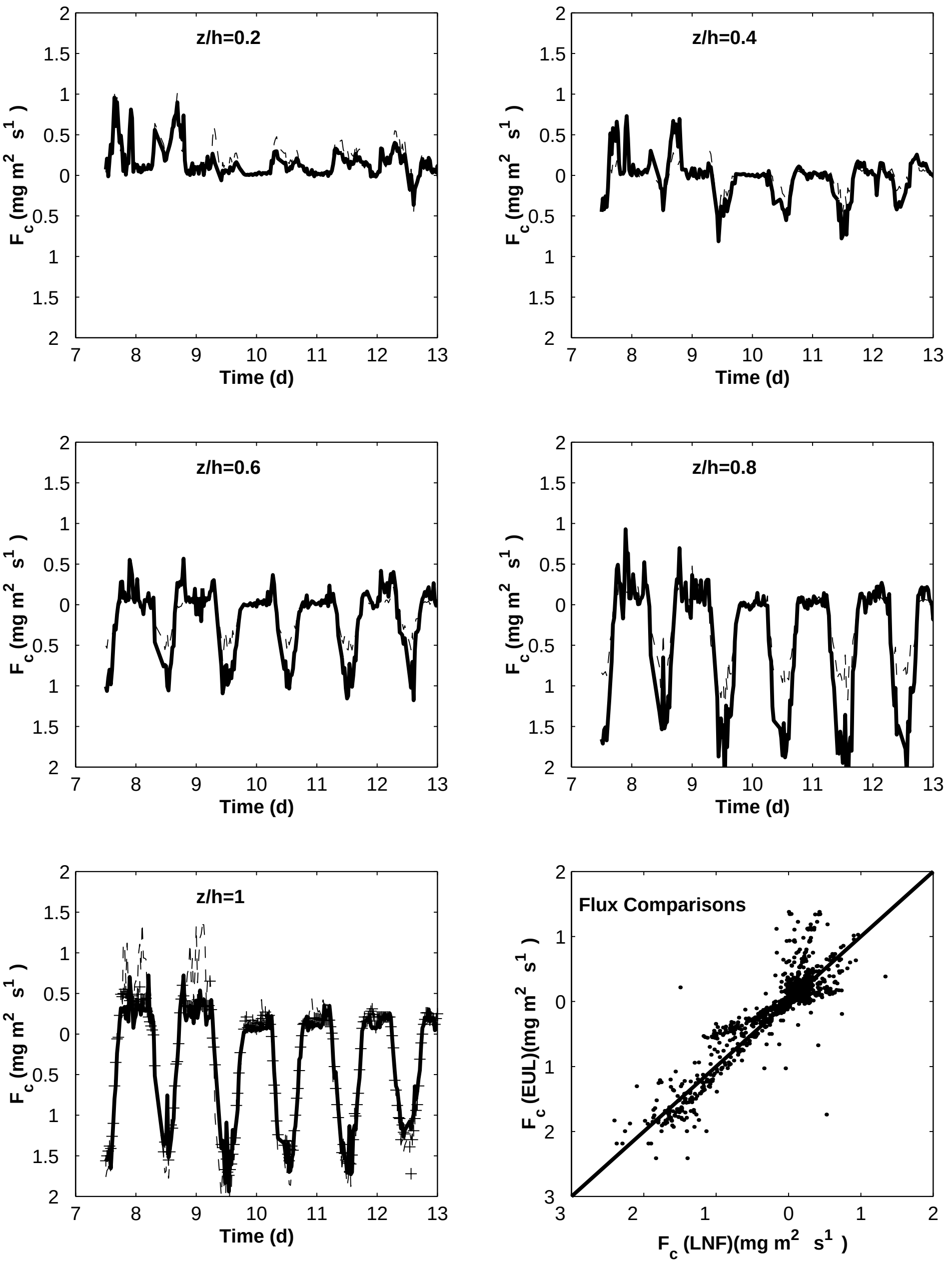

Figure 2. Comparison between Eulerian and *LNF* computed CO_2 fluxes (mg CO_2 m^{-2} s^{-1}) at z/h = 0.2, 0.4, 0.6, 0.8, and 1.0. The dotted-thin line are for the Eulerian method ($C_8 = 8$) while the solid line represents the *LNF* calculations by Leuning (2000). At z/h = 1, the eddy-covariance CO_2 flux measurements (plus) are displayed. The overall comparison between Eulerian and *LNF* CO_2 fluxes along with the 1 : 1 line is also shown.

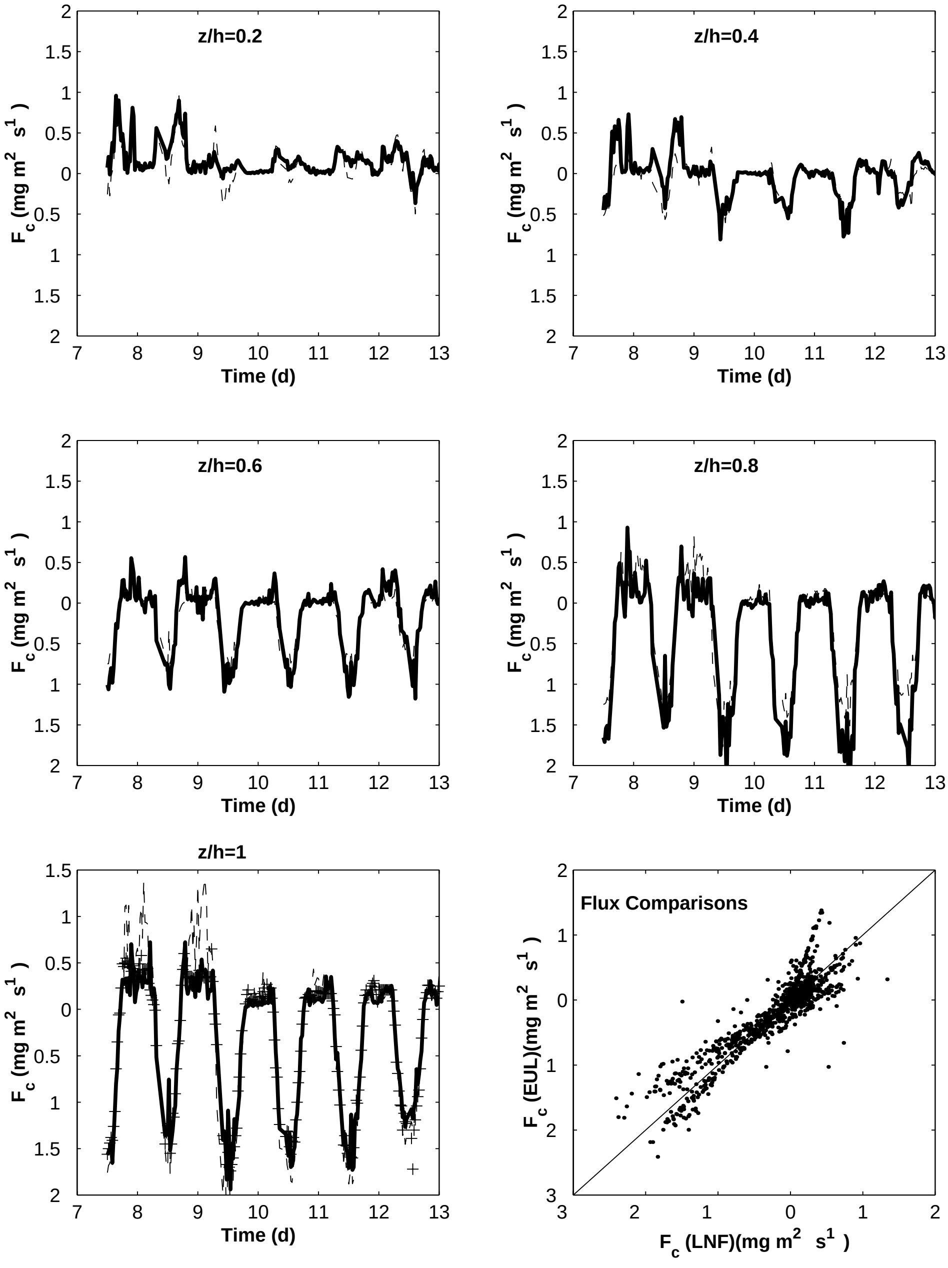

Figure 3. Same as Figure 2 but for $C_8 = 1.5$.

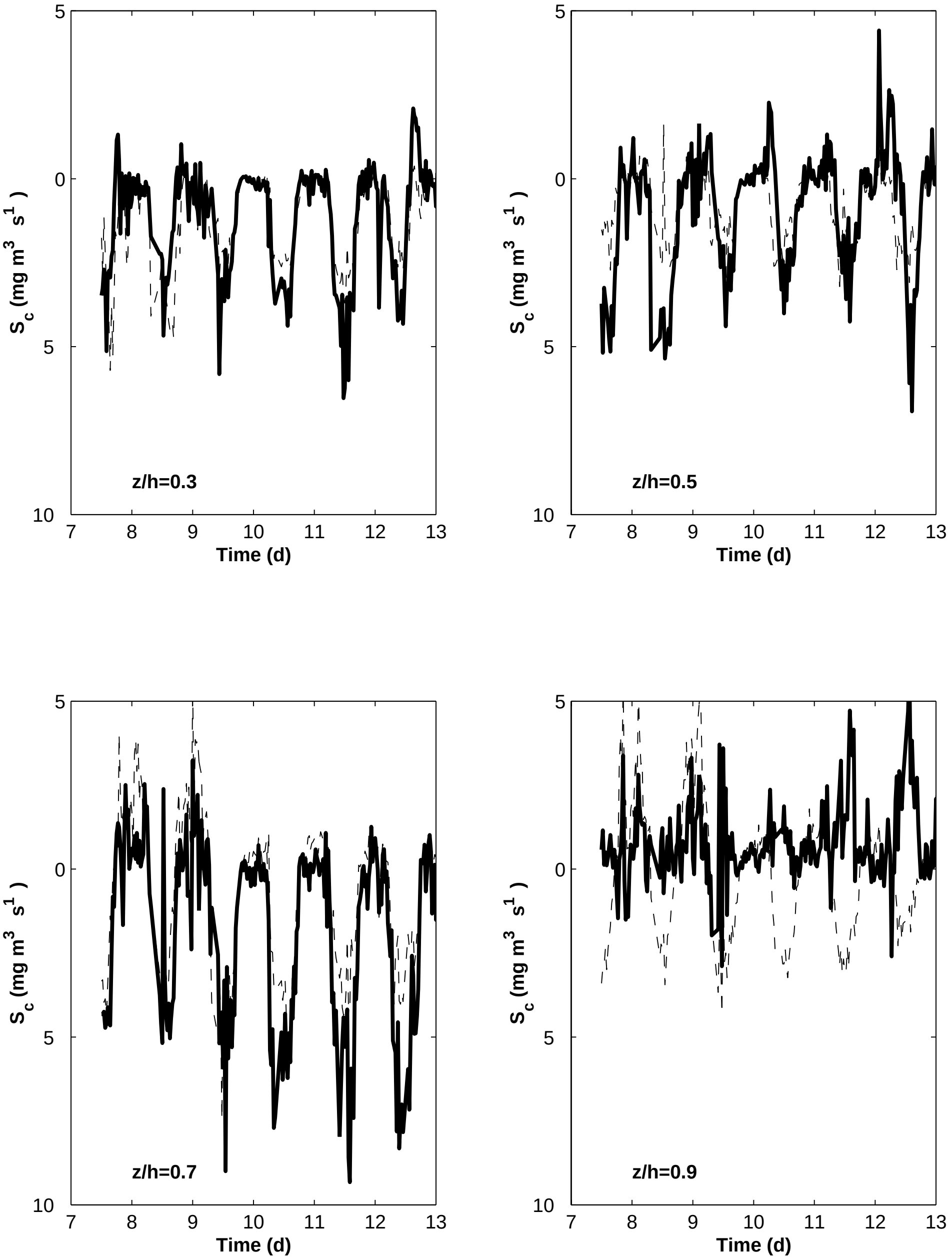

Figure 4. Comparison between Eulerian and *LNF* computed CO_2 sources (mg CO_2 m^{-3} s^{-1}) at z/h = 0.3, 0.5, 0.7, 0.9. The dotted-thin line are for the Eulerian method (C_8 = 1.5) while the solid line represents the *LNF* source calculations by Leuning (2000).

TABLE III

Comparison between *LNF* (F_{LNF}) and the Eulerian (F_{EUL}) computed CO_2 fluxes for $C_8 = 8$ and 1.5, respectively. The regression analysis is $F_{\mathrm{EUL}} = AF_{\mathrm{LNF}} + B$. The coefficient of determination (R^2) and the standard error of estimate (SEE) are shown. The values in brackets are comparison between computed F_{EUL} at z/h = 1 and eddy-covariance CO_2 flux measurements at z/h = 3.3.

C_8	z/h	A	B	SEE	R^2
8.0	0.2	1.02	0.03	0.087	0.88
	0.4	0.50	0.00	0.063	0.81
	0.6	0.47	−0.03	0.068	0.90
	0.8	0.53	0.00	0.115	0.92
	1.0	1.22 (1.20)	0.11 (0.07)	0.220 (0.25)	0.94 (0.92)
1.5	0.2	0.84	−0.01	−0.01	0.77
	0.4	0.66	−0.05	−0.05	0.66
	0.6	0.66	−0.07	−0.07	0.80
	0.8	0.76	0.05	0.05	0.88
	1.0	1.22	0.11	0.11	0.94

lysis predicted a peak in mid-canopy and, surprisingly, respiration in the uppermost 20% of the canopy.

One reason for these differences arises from the nature of the inverse problem itself. Inspection of Equation (6) for the mean vertical flux shows that the coefficient A_4 contains both the first and second derivatives of the scalar concentration. Analyses involving derivatives of experimental data are inevitably sensitive to small errors in measurements, numerical approximations of continuous derivatives, and modelled velocity statistics. Similar considerations apply to the *LNF* analysis.

The large positive values predicted by the Eulerian analysis shown in Figures 2 and 3 for the nights of 7 and 8 August resulted from neglect of the influence of nocturnal stable stratification, whereas this had been incorporated into the *LNF* analysis of Leuning (2000).

Comparison between measured fluxes and those predicted by the Eulerian closure model above the canopy is also shown in Table III (for $z/h = 1$) and shows there was good agreement. Notice that such a comparison is insensitive to the choice of C_8 given the near identical regression statistics for the two values of C_8 in Table III. This insensitivity to C_8 is not surprising given that the flux-transport term above the canopy is small when compared to its value within the canopy. A direct consequence of such comparisons is that good agreement between measured and modeled fluxes above the canopy may not necessarily lead to good agreement within the canopy. Additionally, Figure 5 suggests that flux comparisons are less

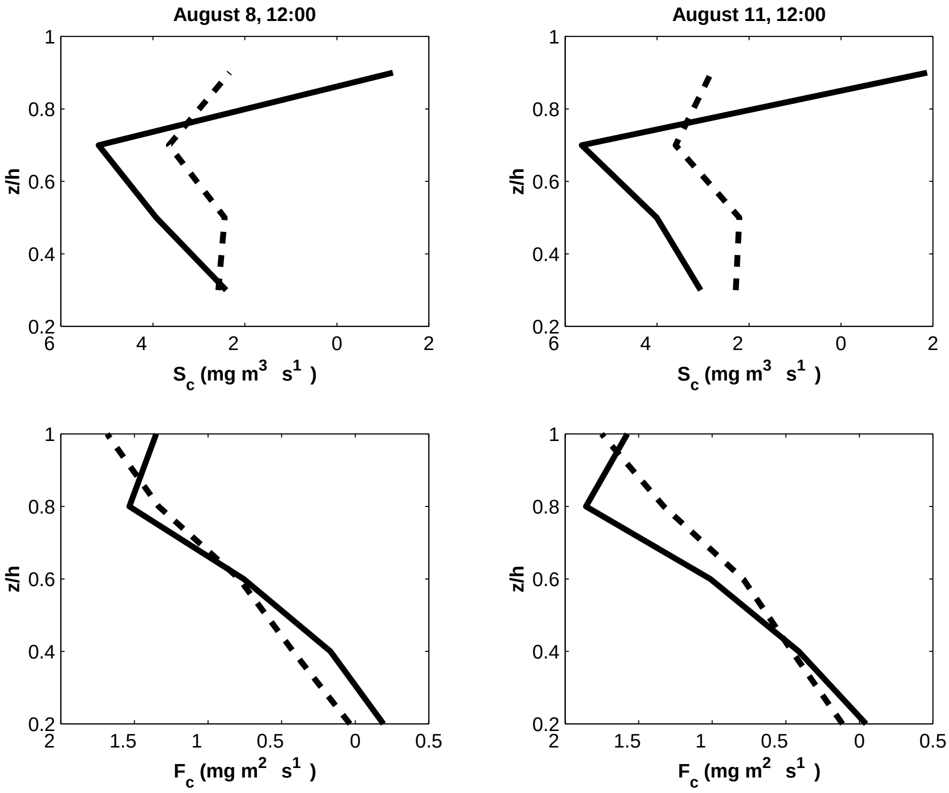

Figure 5. Comparison between Eulerian (dashed line) and *LNF* (solid line) CO_2 source (mg CO_2 m^{-3} s^{-1}) (top panels) and flux (mg CO_2 m^{-2} s^{-1}) (bottom panels) profiles for 8 August (left panels) and 11 August (right panels).

capable of distinguishing the two model performance differences when compared to source comparisons. Again, this is not surprising since scalar fluxes at a given height are related to the integrated sources, and hence, are likely to average-out random source differences between the two models.

5. Conclusions

This study evaluated the use of a coupled second-order closure model for momentum and scalar transport to infer scalar sources from measured mean concentration profiles within a rice canopy. We demonstrated the following:

(1) The second-order closure model of WS77 reproduced well the measured first and second velocity moments within the canopy. However, it poorly reproduced the measured Sk_w inside the canopy, consistent with other studies for taller vegetation (e.g., Katul and Albertson, 1998).

TABLE IV

Comparison between *LNF* (S_{LNF}) and the Eulerian (S_{EUL}) computed CO_2 sources for $C_8 = 1.5$. The regression analysis is $S_{EUL} = A, S_{LNF} + B$. The coefficient of determination (R^2) and the standard error of estimate (SEE) are shown.

z/h	A	B	SEE	R^2
0.3	0.65	−0.43	0.88	0.68
0.5	0.31	−0.44	0.86	0.35
0.7	0.61	0.34	1.51	0.60
0.9	0.20	−0.2	1.93	0.02

(2) The computed maximum CO_2 flux in the lowest layer was larger when the rice field was drained when compared to flooded conditions, consistent with the conclusion of Miyata et al. (2000) that the floodwater provides a barrier to diffusion of CO_2 from the soil to the atmosphere. The computed daytime maximum CO_2 fluxes in the lowest layer differ by a factor of 2 between flooded and drained conditions.

(3) Calculations of flux profiles within the canopy from the Eulerian closure approach are in good agreement with Localized Near Field Theory calculations despite fundamental differences in approximations and simplifications. However, this agreement was achieved only after reducing the magnitude of the closure constant in the flux-transport term from its original value (C_8 = 8) proposed by Andre et al. (1979) to C_8 = 1.5.

(4) Eulerian and *LNF* inverse analyses differed in their predictions of CO_2 *source distributions* within a rice canopy. The second-order closure model indicated a bimodal daytime sink distribution, with maxima in the top and bottom thirds of the canopy. In contrast, the *LNF* analysis predicted a peak in mid-canopy and, surprisingly, respiration in the uppermost 20% of the canopy.

The broader implications of this study is that estimating the source distribution from mean scalar concentrations within the canopy, on a 30-minute time scale, is complicated by many processes that are not well resolved by both Eulerian and Lagrangian methods. Given that the inverse problem is mathematically ill-posed, using both methods to recover the source distribution may provide guidance as to whether such a source is reasonable or not. These approaches are derived using different approximations; hence, agreement between their source calculations adds some confidence in the accuracy of the computed source. Conversely, when these two methods diverge in their source estimation, care must be exercised in interpreting the resulting source distribution and its possible linkage to physiological activity within the canopy. In short, the inverse problem can further benefit from the synergies offered by contrasting both inverse approaches.

Acknowledgements

The authors would like to thank Taejin Choi and Jinkyu Hong for all their help in collecting and processing the velocity measurements during the *IREX* experiment. This study was supported, in part, by the 'Bilateral International Joint Research by Special Fund Promoting Science and Technology (FY1996)', and 'Japanese Study on the Behavior of greenhouse gases and aerosols (FY1990-1999)', by the Research and Development Bureau, Japan and Science Agency. The Australian authors acknowledge support from the Australian Department of Science Multi-function Polis Program for support to travel to Japan in 1995 and to conduct the experiment in 1996. The Korean author acknowledges support from the Korean Ministry of Science and Technology through the National Research Laboratory Program and the Brain Korea 21 Project. The U.S. author acknowledges partial support from the U.S. Department of Energy (DOE) National Institute of Global Environmental Change (NIGEC) through the NIGEC Southeast Regional Center at the University of Alabama, Tuscaloosa, under cooperative agreement DE-FC03-90-ER61010, and the FACE-FACTS project.

Appendix A: Determination of the Closure Constants and Computational Algorithm

This Appendix presents details required for the implementation of the second-order model for momentum transport.

A.1. Determination of a_1, a_2, a_3, and C_w

To determine these constants, the basic equations in the WS77 model are matched asymptotically to reproduce the flow statistics in the atmospheric surface layer (ASL) in the absence of gradients in triple-velocity correlations such that

$$\begin{aligned}
\sigma_u &= A_u u_* \\
\sigma_v &= A_v u_* \\
\sigma_w &= A_w u_* \\
q &= \sqrt{(A_u^2 + A_v^2 + A_w^2)}u_* = A_q u_* \\
\frac{d\bar{u}}{dz} &= \frac{u_*}{kz}; \quad u_*^2 = -\overline{u'w'},
\end{aligned} \tag{A1}$$

where A_u, A_v, and A_w can be obtained from measurements using the sonic anemomenter or from the literature (e.g., Kaimal and Finnigan, 1994; Monin and Yaglom, 1971). Values of a_2, a_3, C_w, α and C_d, presented in Table I, can be derived from A_u, A_v, and A_w as discussed in Katul and Albertson (1999).

A.2. Numerical techniques

The vertical computational flow domain was set to 3.4h, and a Δz = 0.025 m resulted in 96 computational nodes. This grid density was necessary due to the rapid variability in $a(z)$ near $z/h = 0$ and $z/h = 1$. The boundary conditions imposed are:

$$z = 0 \quad \begin{cases} \dfrac{d\sigma_u}{dz} = 0 \\ \dfrac{d\sigma_v}{dz} = 0 \\ \dfrac{d\sigma_w}{dz} = 0 \\ u_* = 0 \\ \langle \bar{u} \rangle = 0 \end{cases} \tag{A2}$$

$$z = 3.4h \begin{cases} \sigma_u = A_u u_* \\ \sigma_v = A_v u_* \\ \sigma_w = A_w u_* \\ u_* = 1 \\ \dfrac{d\langle \bar{u} \rangle}{dz} = \dfrac{u_*}{k(z-d)} \end{cases} ,$$

where u_* is measured using the sonic anemometer at z/h = 3.3. Notice that the boundary conditions for $\langle \bar{u} \rangle$ require the estimation of the zero-plane displacement height (d).

With $\langle \overline{u'w'} \rangle$ profile modelled by WS77, d can be readily computed within the iterative scheme. As discussed in Katul and Albertson (1998) and Katul and Chang (1999), the five ordinary differential equations (ODEs) for the velocity statistics were first discretized by central differencing of all derivatives. An implicit numerical scheme was constructed for each ODE with the boundary conditions stated above. The tridiagonal system, resulting from the implicit forms of these discretized equations, was solved using the *Tridag* routine in Press et al. (1992, pp. 42–43) for each second-order ODE to produce the turbulent statistic profile. Convergence is achieved when the maximum difference between two successive iterations for q did not exceed 0.1%. We ran the closure model for Δz = 0.01 m, 0.02 m, 0.025 m, and 0.05 m and checked that all solutions were nearly independent of Δz. For the scalar transport equations, a vertical mesh was created with Δz = 0.025 m, and the measured CO_2 concentration were linearly interpolated at each node from the measurements at each time step.

Determination of C_4

For an ASL with negligible flux divergence and upon combining Equations (6) and (8), we obtain:

$$\langle\overline{w'c'}\rangle = -2\frac{\tau}{C_4}\langle\overline{w'w'}\rangle\frac{\partial\langle\bar{c}\rangle}{\partial z}.$$

Noting that in the ASL

$$\langle\epsilon\rangle = \frac{u_*^3}{k(z-d)},$$

$$\frac{\partial\langle\bar{c}\rangle}{\partial z} = \frac{\langle\overline{w'c'}\rangle}{u_* k(z-d))},$$

$$\langle\overline{w'w'}\rangle = (A_w u_*)^2,$$

$$q^2 = (A_q u_*)^2,$$

$$\tau = \frac{q^2}{\langle\epsilon\rangle} = 6.5\left(\frac{k(z-d)}{u_*}\right),$$

and that A_w and A_q are 1.25 and 3.82, respectively, results in $C_4 \approx 9.9$ (André et al., 1979; Meyers and Paw U, 1987). However, large eddy simulations by Moeng and Wyngaard (1986) demonstrate that the scalar flux destruction term (with C_4 determined from an analysis analogous to the above) is about a factor of 2–3 too large. For this reason, we reduced C_4 by 3 and assumed $C_4 = 3$ for unstable and near-neutral conditions. With such an assumption, the flux-transport contribution to the scalar flux budget remains significant in the ASL and is consistent with scalar dissipation calculations by Hsieh and Katul (1997). To account for the additional dissipation in stable conditions, we increased the constant C_4 by 1.5 to match the ASL Businger–Dyer stable stability formulations for the eddy diffusivity throughout for stable conditions only.

References

Abdella, K. and McFarlane, N.: 1997, 'A New Second-Order Turbulence Closure Scheme for the Planetary Boundary Layer', *J. Atmos. Sci*. **54**, 1850–1867.

André, J. C., de Moor, G., Lacarrere, P., Therry, G., and du Vachat, R.: 1979, 'The Clipping Approximation and Inhomogeneous Turbulence Simulations', *Turbulent Shear Flow* **I**, 307–318.

Andren, A.: 1990, 'Evaluation of a Turbulence Closure Scheme Suitable for Air Pollution Applications', *J. Appl. Meteorol*. **29**, 224–239.

Canuto, V. M., Minotti, F., Ronchi, C., Ypma, R. M., and Zeman, O.: 1994, 'Second-Order Closure PBL Model with New Third-Order Moments: Comparison with LES Data', *J. Atmos. Sci*. **51**, 1605–1618.

Corrsin, S.: 1974, ‘Limitations of Gradient Transport Models in Random Walks and Turbulence’, *Adv. Geophys.* **18A**, 25–60.

Deardorff, J. W.: 1972, ‘Theoretical Expression for the Countergradient Vertical Heat Flux’, *J. Geophys. Res*. **77**, 5900–5904.

Deardorff, J. W.: 1978, ‘Closure of Second and Third Moment Rate Equations for Diffusion in Homogeneous Turbulence’, *Phys. Fluids* **21**, 525–530.

Denmead, O. T.: 1995, ‘Novel Meteorological Methods for Measuring Trace Gas Fluxes’, *Phil. Trans. Roy. Soc. London A*. **351**, 383–396.

Denmead, O. T. and Bradley, E. E.: 1985, ‘Flux-Gradient Relationships in a Forest Canopy’, in B. A. Hutchinson and B. B. Hicks (eds.), *The Forest-Atmosphere Interaction*, D. Reidel, Norwell, MA, pp. 421–442.

Denmead, O. T. and Raupach, M. R.: 1993, ‘Methods for Measuring Atmospheric Gas Transport in Agricultural and Forest Systems’, in J. M. Duxbury, L. A. Harper, A. R. Mosier, and D. E. Rolston (eds.), *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change,* American Society of Agronomy, Madison.

Donaldson, C. Du P.: 1973, ‘Construction of a Dynamic Model for the Production of Atmospheric Turbulence and the Dispersion of Atmospheric Pollutants, *Workshop on Micrometeorology, Amer. Meteor. Soc*., 313–392.

Finnigan, J. J.: 1985, ‘Transport in Flexible Plant Canopies’, in B. A. Hutchison and B. B. Hicks (eds.), *The Forest-Atmosphere Interaction*, D. Reidel Publishing Company, Norwell, MA, pp. 443–480.

Gibson, M. M. and Launder, B. E.: 1978, ‘Ground Effects on Pressure Fluctuations in the Atmospheric Boundary Layer’, *J. Fluid Mech*. **86**, 491–511.

Hanjalic, K. and Launder, B. E.: 1972, ‘A Reynold Stress Model for Turbulence and its Application to Thin Shear Flows’, *J. Fluid Mech*. **52**, 609–638.

Hsieh, C. I. and Katul, G. G.: 1997, ‘The Dissipation Methods, Taylor’s Hypothesis, and Stability Correction Functions in the Atmospheric Surface Layer’, *J. Geophys. Res*. **102**, 16391–16405.

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

Katul, G. G. and Albertson, J. D.: 1998, ‘An Investigation of Higher Order Closure Models for a Forest Canopy, *Boundary-Layer Meteorol*. **89**, 47–74.

Katul, G. G. and Albertson, J. D.: 1999, ‘Modeling CO_2 Sources, Sinks, and Fluxes within a Forest Canopy, *J. Geophys. Res*. **104**, 6081–6091.

Katul, G. G. and Chang, W.: 1999, ‘Principal Length Scales in Second-Order Closure Models for Canopy Turbulence’, *J. Appl. Meteorol*. **38**, 1631–1643.

Katul, G. G., Oren, R., Ellsworth, D., Hsieh, C. I., Phillips, N., and Lewin, K.: 1997a: ‘A Lagrangian Dispersion Model for Predicting CO_2 Sources, Sinks, and Fluxes in a Uniform Loblolly Pine (*Pinus taeda* L.) Stand’, *J. Geophys. Res*. **102**, 9309–9321.

Katul, G. G., Hsieh, C. I., Kuhn, G., Ellsworth, D., and Nie, D.: 1997b, ‘Turbulent Eddy Motion at the Forest-Atmosphere Interface’, *J. Geophys. Res*. **102**, 13,409–13,421.

Leuning, R.: 2000, ‘Estimation of Scalar Source/Sink Distributions in Plant Canopies Using Lagrangian Dispersion Analysis: Corrections for Atmospheric Stability and Comparison with a Multilayer Canopy Model’, *Boundary-Layer Meteorol*. **96**, 293–314.

Leuning, R., Denmead, O. T., Miyata, A., and Kim, J.: 2000, ‘Source/Sink Distributions of Heat, Water Vapor, Carbon Dioxide, and Methane in a Rice Canopy Estimated Using Lagrangian Dispersion Analysis’, *Agric. For. Meteorol.* **103**, 233–249.

Lewellen, W. S., Teske, M. E., and Sheng, Y. P.: 1980, ‘Micrometeorological Applications of a Second Order Closure Model of Turbulent Transport’, in L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt, and J. H. Whitelaw (eds.), *Turbulent Shear Flows II*, Springer-Verlag, pp. 366–378.

Lumely, J. L.: 1978, ‘Computational Modeling of Turbulent Flows’, *Adv. Appl. Mech*. **18**, 123.

Massman, W. and 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.

Massman, W.: 1997, 'An Analytical One-Dimensional Model of Momentum Transfer by Vegetation of Arbitrary Structure', *Boundary-Layer Meteorol*. **83**, 407–421.

Mellor, G.: 1973, 'Analytic Prediction of the Properties of Stratified Planetary Boundary Layer', *J. Atmos. Sci.* **30**, 1061–1069.

Mellor, G. L. and Yamada, T.: 1974, 'A Hierarchy of Turbulence Closure Models for Planetary Boundary Layers, *J. Atmos. Sci*. **31**, 1791–1806.

Meyers, T. and Baldocchi, D. D.: 1991, 'The Budgets of Turbulent Kinetic Energy and Reynolds Stress within and above Deciduous Forest', *Agric. For. Meteorol*. **53**, 207–222.

Meyers, T. and 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. and Paw U, K. T.: 1987, 'Modelling the Plant Canopy Micrometeorology with Higher-Order Closure Principles', *Agric. For. Meteorol*. **41**, 143–163.

Miyata, A., Leuning, R., Denmead, O. T., Kim, J., and Harazono, Y.: 2000, 'Micrometeorological Measurements of Methane and CO_2 Fluxes over an Intermittently Drained Paddy Field', *Agric. For. Meteorol.*, in press.

Moeng, C. H. and Wyngaard, J. C.: 1986, 'An Analysis of Pressure-Scalar Covariances in the Convective Boundary Layer', *J. Atmos. Sci*. **43**, 2499–2513.

Moeng, C. H. and Wyngaard, J. C.: 1989, 'Evaluation of Turbulent Transport and Dissipation Closures in Second-Order Modeling', *J. Atmos. Sci.* **46**, 2311–2330.

Monin, A. S. and Yaglom, A. M.: 1971, *Statistical Fluid Mechanics*, Vol. 1, MIT Press, Cambridge, MA, 769 pp.

Panofsy, H. A. and Dutton, J. A.: 1984, *Atmospheric Turbulence: Models and Methods for Engineering Applications*, John Wiley and Sons, 397 pp.

Paw U, K. T. and Meyers, T. P.: 1989, 'Investigations with a Higher-Order Canopy Turbulence Model into Mean Source-Sink Levels and Bulk Canopy Resistances', *Agric. For. Meteorol*. **47**, 259–271.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P.: 1992, *Numerical Recipes in Fortran*, 2nd edn, Cambridge University Press, 963 pp.

Raupach, M. R.: 1988, 'Canopy Transport Processes', in W. L. Steffen and O. T. Denmead (eds.), *Flow and Transport in the Natural Environment*, Springer-Verlag, New York, pp. 95–127.

Raupach, M. R.: 1989a, 'Applying Lagrangian Fluid Mechanics to Infer Scalar Source Distributions from Concentration Profiles in Plant Canopies', *Agric. For. Meteorol*. **47**, 85–108.

Raupach, M. R.: 1989b, 'A Practical Lagrangian Method for Relating Scalar Concentrations to Source Distributions in Vegetation Canopies', *Quart. J. Roy. Meteorol. Soc*. **115**, 609–632.

Raupach, M. R. and Shaw, R. H.: 1982, 'Averaging Procedures for Flow within Vegetation Canopies', *Boundary-Layer Meteorol*. **22**, 79–90.

Raupach, M. R. and Thom, A. S.: 1981, 'Turbulence in and above Plant Canopies', *Ann. Rev. Fluid. Mech*. **13**, 97–129.

Raupach, M. R., Antonia, R. A., and Rajagopalan, S.: 1991, 'Rough-Wall Turbulent Boundary Layers', *Appl. Mech. Rev*. **44**, 1–25.

Raupach, M. R., Denmead, O. T., and Dunin, F. X.: 1992, 'Challanges in Linking Atmospheric CO_2 Concentrations to Fluxes at Local and Regional Scales', *Aust. J. Bot*. **40**, 697–716.

Raupach, M. R., Finnigan, J. J., and Brunet, Y.: 1996, 'Coherent Eddies and Turbulence in Vegetation Canopies: The Mixing-Layer Analogy', *Boundary-Layer Meteorol*. **78**, 351–382.

Reynolds, W. C. and Cebeci, T.: 1976, 'Calculation of Turbulent Flows', in P. Bradshaw (ed.), *Topics in Applied Physics: Turbulence*, Springer-Verlag, pp. 193–229.

Shaw, R. H.: 1977, 'Secondary Wind Speed Maxima Inside Plant Canopies', *J. Appl. Meteorol.* **16**, 514–521.

Shaw, R. H. and Pereira, A. R.: 1982, 'Aerodynamic Roughness of a Plant Canopy: A Numerical Experiment', *Agric. Meteorol*. **26**, 51–65.

Shaw, R. H., den Hartog, G., King, K. M., and Thurtell, G. W.: 1974, 'Measurements of Mean Wind Flow and Three-Dimensional Turbulence Intensity within a Mature Corn Canopy', *Agric. For. Meteorol*. **13**, 419–425.

Sreenivasan, K. R., Tavoularis, S., and Corrsin, S.: 1982, 'A Test of Gradient Transport and its Generalization', in L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt, and J. H. Whitelaw (eds.), *Turbulent Shear Flow III*, Springer-Verlag, New York, pp. 96–112.

Thom, A. S.: 1971, 'Momentum Absorption by Vegetation', *Quart. J. Roy. Meteorol. Soc.* **97**, 414–428.

Willis, G. E. and Deardorff, J. W.: 1974, 'A Laboratory Model of the Unstable Planetary Boundary Layer', *J. Atmos. Sci*. **31**, 1297–1307.

Wilson, J. D.: 1988, 'A Second Order Closure Model for Flow Through Vegetation', *Boundary-Layer Meteorol*. **42**, 371–392.

Wilson, J. D.: 1989, 'Turbulent Transport within the Plant Canopy', in *Estimation of Areal Evapotranspiration*, IAHS Publ., No. 177, pp. 43–80.

Wilson, N. R. and Shaw, R. H.: 1977, 'A Higher Order Closure Model for Canopy Flow', *J. Appl. Meteorol*. **16**, 1198–1205.