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Surface renewal analysis: a new method to obtain scalar fluxes

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Abstract

A new method for estimating scalar fluxes, called surface renewal analysis, was developed and successfully tested with air temperature data from a maize crop, an orchard, and a forest canopy. The method employs the scalar trace and is based on the concept of turbulent coherent structures causing most of the scalar fluxes. It was generally more accurate than other scalar based methods such as the Tillman variance method, and can be applied to data gathered under stable stability conditions. Filtering the temperature trace, based on the wind speed at the canopy height, resulted in more accurate surface renewal estimates than when raw 10 Hz data were used.

1. Introduction

Numerous methods exist for estimating the flux density of scalars. Eddy covariance (in this paper, we will refer to the estimation of sensible heat flux density from $\overline{w'T'}$ as the eddy covariance method, because the more commonly used term 'eddy correlation' is not strictly correct) requires the collocation of fast response sensors for scalars and the vertical wind velocity. Aerodynamic methods involve obtaining the mean profile of the scalar and wind velocity. The Bowen Ratio–Energy Budget method involves estimating scalar heat fluxes (sensible heat and latent energy flux densities) with a gradient of temperature and humidity, coupled with net radiation and ground heat flux density measurements. The fetch requirement for each of these

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methods is formally greater than 100 times the height of the measurements, although lesser fetches are frequently available in practice.

Estimation of scalar fluxes without using high frequency velocity signals (such as those needed for eddy covariance) is of interest because (1) fast response anemometers are expensive and are not always available; (2) low wind speeds may compromise the accuracy of methods such as eddy covariance; (3) the velocity data can be compromised by mounting or sensor head distortion or because of other reasons; (4) using scalar signals without high frequency velocity data reduces the number of instruments required; (5) for the case of sensible heat flux density, the cost could be very low. In addition, if surface renewal analysis is reasonably accurate, this would support the concept that turbulent coherent structures play a significant role in plant canopy–atmosphere exchange.

Two decades ago, Tillman (1972) suggested that under unstable conditions, the variance of a scalar alone might be sufficient to estimate the scalar flux density. More recently, Weaver (1990) and Lloyd et al. (1991) found that sensible heat flux was reasonably estimated using temperature variance and similarity, in the cases of semi-arid grasslands and brush. Weaver's (1990) method required measurements of mean wind speed at several heights in addition to the temperature variance. Although inexpensive, cup anemometers require careful calibration and leveling to operate accurately, which would be of great importance when gradients are needed. Use of this method also requires obtaining the wind profile above the roughness sublayer, which limits the usefulness of such a method over tall canopies such as forests and some orchards. In addition, tables in his article showed that the coefficients relating the flux to the variance were not constants, but rather varied by up to 100%, depending on the surface and energy budget. Lloyd et al. (1991) used a version of Tillman's (1972) expressions and found standard errors of the estimate ranging from 18 to 45 W m^{-2} over such surfaces as tiger bush, savannah, and millet fields. Similar success was obtained by De Bruin et al. (1993) for the stone, pebble and sparsely vegetated surface of La Crau, France, where instruments were far above the roughness sublayer.

In this paper, the concept of turbulent coherent structures, which have been identified as ubiquitous in near-canopy flows (Bergström and Högström, 1989; Gao et al., 1989; Shaw et al., 1990; Paw U et al., 1992), is used to develop a form of surface renewal analysis. The fast response temperature trace is used to estimate the scalar sensible heat flux density, with the estimates validated against eddy covariance.

2. Surface renewal analysis theory

In surface renewal analysis, a parcel of air is assumed to originate above the canopy with a characteristic scalar value. To simplify matters, in this paper air temperature will be used as the scalar to exemplify the method concretely; however, the methodology would be the same for any scalar including trace gas concentrations.

The parcel instantaneously penetrates or sweeps into the canopy and begins to be heated by the canopy (if the leaves and canopy elements are warmer than the air). The expected temperature pattern observed by a sensor at the canopy height would therefore be a sudden temperature drop when the parcel penetrated the canopy, and then a gradual temperature rise as the canopy heated the air (see Fig. 1). The repeated sawtooth patterns shown in Fig. 1 are called 'ramp events'. Conversely, if the canopy elements were to be cooler than the air, then the initial sweep of air would be seen as a sudden rise in the temperature trace, with a slow cooling following this rise.

Paw U (1990) and Paw U and Brunet (1991) used a form of surface renewal analysis by assuming that under unstable conditions (canopy warmer than the air), any temperature rise in the temperature signal represents air being heated by the canopy, and that under stable conditions (canopy cooler than the air), any temperature drop represents air being cooled by the canopy. If the parcel of air is defined to have a volume V, then the temperature change rate with time ($\mathrm{d}T/\mathrm{d}t$) can be shown to be directly related to the sensible heat flux H

$$H = \rho C_\mathrm{p} \frac{\mathrm{d}T}{\mathrm{d}t}\left(\frac{V}{A}\right) \tag{1}$$

where ρ is the air density, C_p is the specific heat per unit mass at constant pressure, and the other terms have been previously defined except the ratio (V/A), which represents the volume of the parcel over the horizontal area at the parcel base. This ratio converts the heating rate per unit volume (W m^{-3}) of the parcel into a sensible heat flux density (W m^{-2}). It can be seen that if the vertical dimension of the parcel is considered to be the height of the canopy, that the ratio (V/A) is equal to the canopy height h. The general validity of Eq. 1 holds for both small control volumes and for larger volumes, so long as the heat flux density H is properly interpreted.

Our surface renewal analysis scheme is far simpler than the type developed by Higbie (1935) and Danckwerts (1951), and later by Brodkey et al. (1978), Komori et al. (1982), Asher and Pankow (1991), and others. In that type of scheme, assumptions are made concerning the contact time of a fluid parcel next to a surface, and the

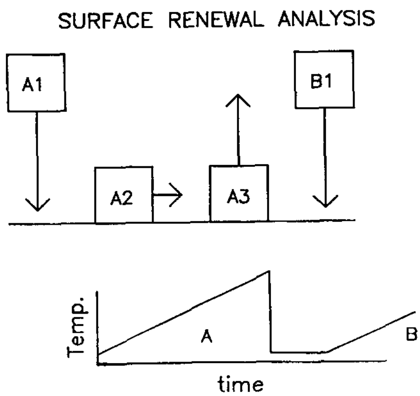


Fig. 1. Idealized paradigm of surface renewal sensible heat flux. Parcel 'A' descends in stage 'A1' to the plant canopy, where ('A2') it is heated by the plant elements, and then in stage 'A3' it instantly ascends. At that moment, parcel 'B' instantly descends in stage 'B1' and begins heating. An idealized temperature trace with time is shown below the parcel movement schematic.

diffusive processes which exchange heat or other fluxes during this contact time. Exchange processes are centered at the lower surface of the parcel. In our scheme, we ignore the details of the diffusive mixing within the parcel. However, we make the same assumption, that negligible heat is lost from the parcel top, as in most previous surface renewal paradigms. This last assumption is clearly an idealization that is not easily testable because of the Lagrangian nature of the model.

This assumption is partially supported by the fact that direct heat exchange can only occur at heights less than or equal to the plant canopy height, where the canopy elements exist. In our scheme, heat is added throughout the parcel height, and then the entire parcel is replaced by another parcel of air at the same ground location. The area of this parcel which has been replaced is used in the estimation of the sensible heat flux density.

Unfortunately, the above equation formally requires the measurement of the total derivative of temperature with respect to time ($\mathrm{d}T/\mathrm{d}t$), but a fixed temperature sensor can only measure the partial derivative. The relationship between the two derivatives is

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} \tag{2}$$

where the equation has been formulated for only the x-direction. It should be noted that in this manuscript, we refer to the last term in Eq. 2 as an advective term, not to be confused with the 'advective' defined in some agricultural meteorology works as the advection of warm, dry air over a cooler, transpiring surface, nor with the concept of mean advection where a mean wind velocity is multiplied by a mean temperature gradient.

It should also be noted that although Eq. (2) is rigorously true for infinitesimally small volumes, we have applied it for macroscopic parcels of a size characteristic of the coherent structures identified by Gao et al. (1989) and Paw U et al. (1992). Application to the larger scales may be understood by considering a volume averaging operation similar to that discussed by Raupach and Shaw (1982), analogous to Reynolds decomposition-related averaging in time. Such an operation would yield an expression with averaged local time derivative and 'advective' terms, with the 'advective' terms being assumed to be the higher frequency terms, as before.

Paw U and Brunet (1991) assumed that for the unprocessed high frequency temperature trace, the advective term was linearly proportional to the total derivative. The local time derivative was estimated by fast response temperature sensors at canopy height. The temperature reading at one time was subtracted from the succeeding reading, and then divided by the time interval between readings (0.1 s), to obtain a simple finite difference, local time derivative. This value was divided in half to give a crude value representing the averaged temperature change of the canopy air (see Eq. (3) below). One could interpret this as assuming no air temperature change at the ground surface, with a linear temperature change to the canopy top.

The surface renewal heat fluxes of each of the estimated temperature derivatives were summed, and then averaged for the half hour period corresponding to an experimental run. Separate averages were calculated, one for positive temperature derivatives, representing unstable conditions, and one for negative temperature derivatives, representing stable conditions. Stability type was then determined from the sign of the eddy covariance measurements. In practical usage, for the surface renewal method (without supporting covariance measurements), third-order structure functions (Van Atta, 1977; Antonia et al., 1981) or mean temperature gradients could be used to determine stability type instead.

The overall method led to the result that

$$H = \frac{\alpha}{2}\rho C_{\mathrm{p}}\frac{\partial T_{\mathrm{m}}}{\partial t}\left(\frac{V}{A}\right) + B \tag{3}$$

where α and B are regression coefficients fit to the above equation when H is measured by independent means such as eddy covariance, and $\partial T_{\mathrm{m}}/\partial t$ represents the average temperature derivative for either stable or unstable conditions. The coefficients α and B would be a function of the effects of advection on the temperature trace, as well as the general frequency response of the temperature sensors (the latter point was noted by Professor Roger Shaw during a discussion on the technique). This method was used in this paper as a first test of the applicability of surface renewal analysis.

It should be noted that the flux of any scalar quantity could be estimated in a similar manner as above, where temperature is replaced by the relevant scalar quantity (such as trace gas concentration), and sensible heat flux density by the relevant scalar flux (such as trace gas flux density).

A second method was to filter the data with a band-pass 6th order Butterworth filter (Otnes and Enochson, 1978). After filtering, the mean $\partial T_{\mathrm{m}}/\partial t$ was estimated in the same manner as for the unfiltered surface renewal method.

Filtering was performed under the assumption that the unwanted advective terms in Eq. (2) are the main contributors to the high frequency scalar trace. This was based on several reasons. Firstly, it is generally accepted that the high frequency components do not contribute greatly to fluxes in the surface layer. Secondly, the kinematic nature of the advective term, which involves the product of the instantaneous velocity and spatial temperature gradient, is postulated to result in higher frequencies than the total time derivative of the parcel temperature. If the velocity and temperature gradients are thought of as waves with frequencies ($e^{\mathrm{i}\omega 1\mathrm{t}}$, $e^{\mathrm{i}\omega 2\mathrm{t}}$) for example, the product of the velocity and temperature will have a frequency on the order of the sum of the two individual frequencies ($\omega 1 + \omega 2$). Thirdly, in real data, relatively sharp gradients resulting in high frequency traces, caused by the advection of the parcel from above into the canopy, will occur near the boundaries of coherent structures.

Thus in the surface renewal paradigm, only the intermediate frequency changes within the structures represent the signal which is associated with energy exchange. From energy conservation principles, the total derivative $\mathrm{d}T/\mathrm{d}t$ results from the energy exchange with the parcel over the time of residence in the plant canopy, which is not expected to involve very high frequencies. It was also thought that low frequency drift, characteristic of a slow planetary boundary layer heating and instrumental drift, could contribute spurious amounts of estimated heat flux.

Therefore, band pass filtering would ideally result in an α close to 1 and a B close to 0. The general filtering scheme involved choosing a band pass with a center frequency based on the coherent structure frequency scaling of Paw U et al. (1992). The band pass width was arbitrarily chosen as a decade (i.e. the high cutoff frequency was ten times the low cutoff frequency). After filtering the temperature trace data, the explicit finite difference form of $\partial T/\partial t$ was calculated by subtracting one point from the preceding point, and dividing by the time interval between the points (1 s).

The band pass limits were determined based on the frequency scaling of Paw U et al. (1992) and Raupach et al. (1989). Using a typical mean shear value for a particular canopy (in the first case, the maize canopy), a frequency f was chosen from Paw U et al. (1992). A Strouhal number S (a non-dimensional frequency) was then defined as fh/u, where h is the canopy height and u in the mean wind speed. Upper and lower cutoff Strouhal numbers (representing upper and lower cutoff frequencies) were estimated such that the square root of the product of the upper cutoff frequency times the lower cutoff frequency equalled the Strouhal number S (see Table 1). It was assumed that for the particular canopy, the upper and lower Strouhal numbers were essentially constant. This represented approximating the frequency vs. shear curve of Paw U et al. (1992) in a linear fashion for each canopy type. Therefore, for any wind speed, the upper and lower cutoff frequencies equaled the cutoff Strouhal numbers multiplied by u/h. For example, if the mean wind speed was 2.6 m s^{-1} at the maize canopy height, the lower cutoff frequency would be calculated to be 0.0072 Hz. For a mean wind speed of 5.2 m s^{-1}, the lower cutoff frequency would be 0.0144 Hz.

The filtering frequencies for the walnut orchard and the Borden forest data were chosen in a semi-empirical manner based on the above Strouhal number method. The results of the mean shear vs. frequency scaling from Paw U et al. (1992), and the average mean wind shear from a small subset of data (10 half-hour periods for the orchard data, and 28 half-hour periods for the forest data), were employed to estimate a preliminary frequency. As with the maize case, the upper and lower cutoff frequencies were determined with this preliminary frequency as the logarithmic average. With these small subsets of data, the upper and corresponding lower frequencies were shifted slightly to yield the best regression analysis. The band-pass cutoff Strouhal numbers are shown in Table 1. The cutoff Strouhal numbers straddled the general relationship shown in Paw U et al. (1992), despite the fact that they were partially based on empirical fitting to a few data points.

No attempt to alter the cutoff frequencies based on stability was carried out, because the current paradigm for the turbulent coherent structures is based on mean shear as being the controlling variable (Paw U et al., 1992). Some evidence of

Table 1
Cutoff frequencies for filtering data

Canopy	Lower cutoff Strouhal number	Mean Strouhal number (based on log average)	Upper cutoff Strouhal number
Maize	0.0072	0.023	0.072
Walnut	0.0105	0.033	0.105
Mixed deciduous	0.0124	0.039	0.124

stability effects on the general Fourier spectrum of velocity variance is generally accepted, but at the moment there are insufficient data for stability effects on the occurrence of turbulent coherent structures.

3. Variance methods

We tested Tillman's (1972) variance method by obtaining the Monin–Obukhov lengths estimated from eddy covariance sensible heat flux densities and friction velocities. The temperature variance and standard deviation were calculated for several heights within and above the canopies, based on the fast response thermometer data for each half-hour period. No attempt was made to correct the Monin–Obukhov length for water vapor flux, because generally the water vapor flux would not be measured by researchers using the Tillman method for sensible heat flux estimates. In the original 1972 paper, Tillman did not use vapor flux correction. In the current set of experiments described here, vapor flux was not always measured. Although the Tillman method was developed only for unstable conditions, we tested both variance methods for all stability conditions.

In the Tillman (1972) method, the heat flux under unstable conditions is equal to

$$H = \rho C_{\mathrm{p}} \sqrt[2]{\left(\frac{\sigma_\theta}{C_1}\right)^3 \left(\frac{kgz}{\theta}\right) \left(\frac{C_2 - \frac{z}{L}}{(-\frac{z}{L})}\right)} \tag{4}$$

where σ_θ is the standard deviation of the temperature fluctuations, $C_1 = 0.95$ and $C_2 = 0.0549$ for the range of z/L from −60 to −0.03 (experimentally determined by Tillman (1972)), k is the Von Karman constant, g is the gravitational acceleration, z is the height of measurement, θ is the air temperature in K and L is the Monin–Obukhov length.

In estimating the similarity variable, we used both $(z - d)/L$ and (z/L), with a value of 0.65 h for the zero plane displacement d. We recognized that it was not clear that $(z - d)/L$ would be superior to (z/L), because the zero plane displacement for heat may vary greatly (depending on how it is defined) because of the multilevel nature of plant biometeorology (Paw U and Meyers, 1989). For the sake of brevity, we have omitted the details of this comparison from our tables.

We also tested the hypothesis that sensible heat flux is a function of temperature variance (as expressed by the standard deviation of temperature). We did not account for similarity in this hypothesis. We hypothesized that a linear regression of sensible heat flux vs. standard deviation of temperature might yield reasonable results.

In both the above methods, and the surface renewal method described earlier, no information on stability type (unstable or stable) is explicitly known within the methodologies. Instead, an independent identification technique is required, such as a crude temperature profile or the use of structure functions (Van Atta, 1977; Antonia et al., 1981). In this paper, the stability type was known a priori from the sign of the measured eddy covariance.

4. Experimental description

We used data recorded during four separate experiments conducted over and within three types of plant canopies: maize (*Zea mays*), an English walnut (*Juglans regia*) orchard, and a mixed deciduous forest. The details of the experiments for the first two plant canopies are described by Paw U et al. (1992) and the details for the mixed deciduous forest experiment are given by Neumann et al. (1988) and Shaw et al. (1988).

The maize experiment was carried out in Davis, California, USA (38°32′N, 121°46′W) in August and September 1988 (2.6 m canopy height). The walnut orchard (canopy height 6 m) experiment was carried out between June and August 1989 in Winters, CA (38°31′N, 121°56′W). The mixed deciduous forest (canopy height 18 m) experiment was carried out in the Camp Borden Forest, near Toronto, Ontario, Canada (44°19′N, 80°56′W).

In all experiments, uniaxial sonic anemometers with fine thermocouple thermometers and/or triaxial sonic anemometers were mounted at several heights within and above the plant canopy. For the maize canopy, the thermocouple sensors employed were at 2.6 m and 3.4 m. Although data were also gathered above 3.4 m, surveys of eddy covariance data revealed that inadequate fetch may have occurred even during wind directions associated with maximized fetch for higher levels. Data from temperature sensors at 6.0 m and 12.0 m were used from the Walnut canopy experiment. In both the maize and the walnut canopies, the fetch was best in a generally southerly direction, so the instruments were set up pointing in that direction. The forest canopy had temperature sensors at numerous levels, but those used here were at 18 m and 43 m.

Supporting mean profile measurements for temperature were taken with double-shielded aspirated thermometers. Data were grouped into half-hour periods, for which eddy covariance fluxes were calculated, and 10 Hz fast response temperature and velocity data were saved. Data taken from hundreds of hours of experiments were sifted through to determine if the wind directions were within ±45–90° of the direction in which the sonic anemometers were pointed. This was done to minimize any tower and sensor probe interference effects, and to maximize fetch.

5. Results and discussion

5.1. The maize canopy

The Davis and Winters summer climate of hot, dry days with generally north to northwest morning winds and south to southwest afternoon and night-time winds were associated with a diurnal pattern of stability. After sunrise, the atmosphere would be unstable until near noon; frequently the winds would be northerly and therefore not acceptable for experimental analysis. After 1–2 h of near-neutral conditions, in the mid-afternoon the strong evapotranspirational cooling from the irrigated vegetation would create stable conditions, frequently with southerly winds.

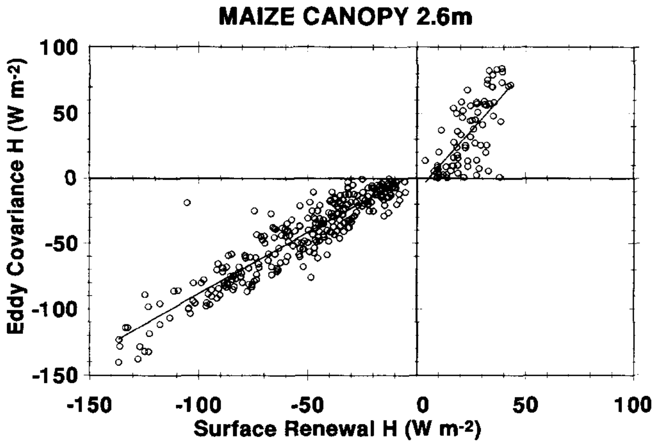


Fig. 2. Eddy covariance sensible heat flux density (H) vs. H estimated using surface renewal analysis with filtered temperature data, for the maize canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

After sunset, stable conditions were maintained by radiational cooling of the vegetative elements. This climatology, coupled with the experimental design, resulted in fewer data gathered during unstable conditions than stable conditions.

The slope for the filtered surface renewal analysis under stable conditions with a sensor height of 2.6 m was close to 1 for the stable case (0.99) with a low standard error of the estimate (11 W m^{-2}) and $r^2 = 0.87$ (Fig. 2 and Table 2). Data from the higher level (3.4 m) resulted in a decrease in accuracy, with $r^2 = 0.83$, a standard error of 12 W m^{-2} and a slope of 1.06. These regression coefficients and standard errors are well within the range found when two eddy covariance/correlation devices are run together over the same canopy, based on the personal experience of the first author.

The unstable case for maize showed substantially higher errors (Figs. 2 and 3, Table 2). Filtered data resulted in a standard error of 19 W m^{-2} and a slope of 2.51, for the sensor at 2.6 m. The higher level of 3.4 m showed a decrease in accuracy with $r^2 = 0.37$ and a standard error of 21 W m^{-2}.

Table 2
Regression coefficients for surface renewal, maize canopy

Stability	Filter	Height (m)	r^2	Standard error (W m^{-2})	a	b (W m^{-2})	n
Stable	No	2.6	0.72	16	0.035	4.2	155
Stable	Yes	2.6	0.87	11	0.99	7.0	155
Stable	No	3.4	0.63	16	0.026	4.4	155
Stable	Yes	3.4	0.83	12	1.06	11	155
Unstable	No	2.6	0.59	17	0.047	−37	41
Unstable	Yes	2.6	0.46	19	2.51	−28	41
Unstable	No	3.4	0.59	17	0.043	−42	41
Unstable	Yes	3.4	0.37	21	1.53	−3.8	41

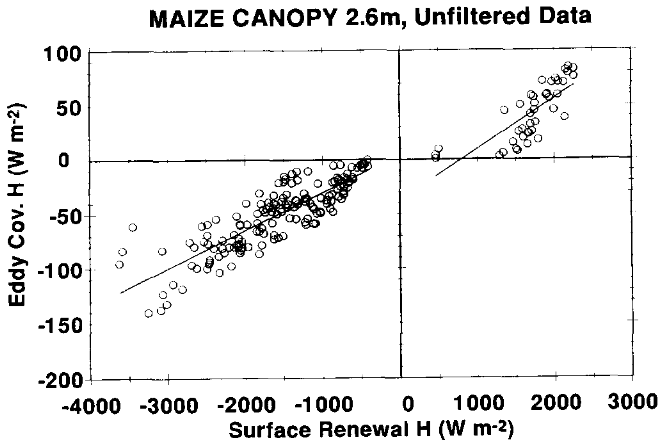


Fig. 3. Eddy covariance sensible heat flux density (H) vs. H estimated using surface renewal analysis with unfiltered 10 Hz temperature data, for the maize canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

Regression of sensible heat flux density obtained from the surface renewal method with unfiltered temperature data yielded reasonable fits, although a moderate amount of scatter is apparent for the maize canopy (Fig. 3 and Table 2). For stable conditions and a sensor height of 2.6 m, the unfiltered data resulted in a standard error of 16 W m^{-2} with $r^2 = 0.72$. At the higher level of 3.4 m, the r^2 was lower, at 0.63. The slope of the unfiltered data was much less than one (0.028–0.035) because high frequency random turbulence, much of which could have been small scale advective phenomena, produced large amounts of apparent heat flux. However, the reasonable fit of the regression partially vindicates the crude assumption noted earlier of a linear relationship between the advective terms and the total derivative.

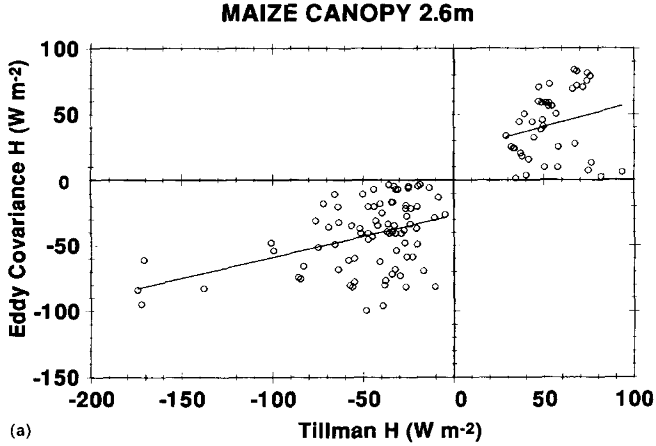
The unfiltered data for unstable conditions yielded slopes higher than those for the

Table 3
Regression coefficients for Tillman method, maize canopy

Stability	HT (m)	r^2	Standard error (W m^{-2})	a	b (W m^{-2})	n
Stable	2.6	0.17	24	0.32	−27	83
Stable	3.4	0.03	21	0.13	−30	111
Unstable	2.6	0.05	25	0.37	22	41
Unstable	3.4	0.04	26	0.22	34	41
$\|H\| > 15$ W m^{-2}						
Unstable	2.6	0.50	11	1.11	−7.0	25
Unstable	3.4	0.58	15	1.03	−12	28
$\|H\| > 15$ W m^{-2}; (z/L)						
Unstable	2.6	0.70	12	0.892	−17	25
Unstable	3.4	0.69	13	0.819	−15	28

stable condition data (0.043 and 0.047, for 2.6 m and 3.4 m, respectively), with little difference in accuracy for the two heights.

The finding that the accuracy for unstable conditions was worse than for stable conditions may indicate that the turbulent advective components were larger for the unstable case. The temperature trace is generally smoother under stable conditions, compared with unstable conditions, over crop canopies (see Paw U et al., 1992), so that the surface renewal method might be expected to perform better with the smoother trace. In addition, it is interesting to note that when data were not screened for wind directions leading to maximum fetch, the accuracy of the regression fits (not listed in the table for the sake of brevity) was very similar to that of acceptable fetch data.



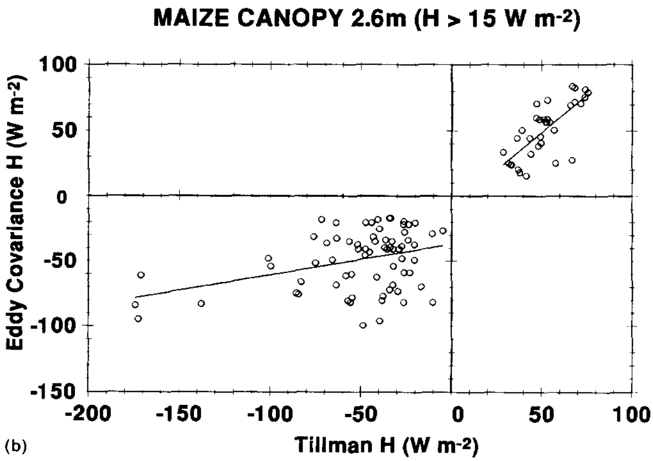


Fig. 4. (a) Eddy covariance sensible heat flux density (H) vs. H estimated using the Tillman method for the maize canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables. (b) Eddy covariance sensible heat flux density (H) vs. H estimated using the Tillman method for the maize canopy, with $|H| < 15$ W m^{-2} excluded from the graph. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

An undesirable feature of the surface renewable analysis, for both filtered and unfiltered data, is that a 'zero-gap' appears with a non-zero y-intercept. This is caused by a residual 'noise' element of temperature changes, probably related to the advective terms, which results in local temperature changes with time, not associated with sensible heat flux exchange.

The Tillman (1972) method worked poorly for all stability conditions with r^2s less than 0.17 (Table 3), unless data points corresponding to low eddy covariance/correlation measurements were omitted arbitrarily (Fig. 4 and Table 3). When data for which eddy covariances were under 15 W m^{-2} were omitted, the regressions for unstable conditions resulted in an improved fit. Estimates under stable condition did not improve substantially and were omitted for the sake of brevity. Using data gathered at 3.4 m resulted in slightly more accurate regression coefficients, because similarity is not expected to work well within or close to the roughness layer caused by the plant canopy. Unexpectedly, the regressions for heat flux density estimates made using (z/L) were more accurate for unstable conditions than those estimates made using $(z-d)/L$ (Table 3).

Use of the standard deviation in place of the Tillman method yielded regression coefficients, implying higher accuracy (Table 4), for both stable and unstable conditions. When data with eddy covariance values lower than 15 W m^{-2} were omitted arbitrarily, unstable conditions had coefficients similar to the best filtered surface renewal method results (for stable conditions), with $r^2 = 0.79$ and a standard error of 11 W m^{-2} (Fig. 5 and Table 4). The stable condition regression was appreciably better than the Tillman method, but worse than the surface renewal method.

Table 4
Regression coefficients for variance method, all canopies for sensible heat flux density vs. temperature standard deviation

Stability	r^2	Standard error (W m^{-2})	a (W m^{-2} K^{-1})	b (W m^{-2})	n
Maize					
Stable	0.46	23	−105	12.6	139
Unstable	0.53	18	180	−42.4	41
$\|H\| > 15$ W m^{-2}					
Stable	0.42	21	−94	2.1	122
Unstable	0.79	11	208	−45.7	25
Walnut					
Stable	0.02	26	−12.3	−38.8	37
Unstable	0.74	31	262	−29.9	24
Forest					
Stable	0.03	28	−41.7	−19.6	113
Unstable	0.27	68	253	13.8	170
$\|H\| > 20$ W m^{-2}					
Stable	0.05	25	−86.0	−31.5	48
Unstable	0.18	58	204	54.5	136

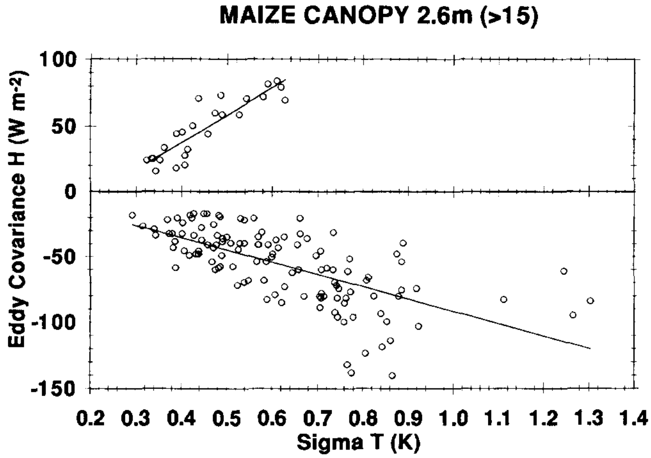


Fig. 5. Eddy covariance sensible heat flux density (H) vs. the standard deviation of temperature showing the temperature variance method for the maize canopy, with $|H| < 15$ W m^{-2} excluded from the graph. Solid lines represent a linear regression best fit, with the regression coefficients given in the Tables.

5.2. *The walnut canopy*

The surface renewal method based on filtered data for the walnut canopy showed slightly greater errors for stable conditions than for the maize canopy (Fig. 6, Table 5). The data yielded a regression slope of 0.66, $r^2 = 0.66$ and a standard error of 16 W m^{-2}. For unstable conditions, the accuracy was similar to that for the stable conditions in terms of r^2, but the standard error was larger (45 W m^{-2}). The r^2 was slightly better than for maize data, but the standard error was worse (19 W m^{-2} for maize).

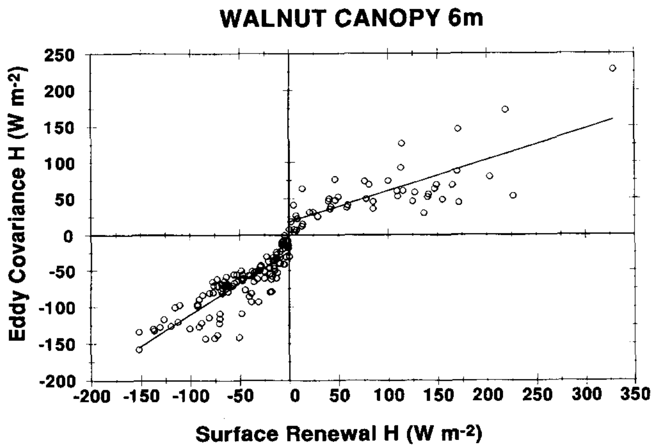


Fig. 6. Eddy covariance sensible heat flux density (H) vs. H estimated using surface renewal analysis with filtered temperature data, for the walnut canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

Table 5
(a) Regression coefficients for surface renewal, walnut canopy

Stability	Filter	r^2	Standard error ($W m^{-2}$)	a	b ($W m^{-2}$)	n
Stable	No	0.34	22	0.015	−8.2	43
Stable	Yes	0.66	16	0.66	−0.1	43
Unstable	No	0.44	59	0.034	12.9	35
Unstable	Yes	0.68	45	1.42	5.5	35

(b) Regression coefficients for Tillman method, walnut canopy

Stability	Height (m)	r^2	Standard error ($W m^{-2}$)	a	b ($W m^{-2}$)	n
Stable	6	0.00	27	0.0	−46	32
Stable	12	0.00	30	0.01	−51	22
Unstable	6	0.63	36	1.57	−54	24
Unstable	12	0.60	25	1.15	−36	13
$\|H\| > 20 W m^{-2}$						
Unstable	6	0.60	37	1.55	−51	23

Unfiltered data gathered under stable conditions also yielded more scattered results than for the maize case (Table 5). The slope was less, with a value of 0.015 $W m^{-2} K^{-1}$ compared with 0.026–0.035 $W m^{-2} K^{-1}$ for maize. Unfiltered data for unstable conditions yielded results paralleling those for filtered data. The slope (0.034) was slightly greater than the stable case, and was less than that for the maize canopy (0.043–0.047) for unstable conditions.

As with the maize data, accepting data from all wind directions including those with poor fetch resulted in regression coefficients ($r^2 = 0.75$, standard

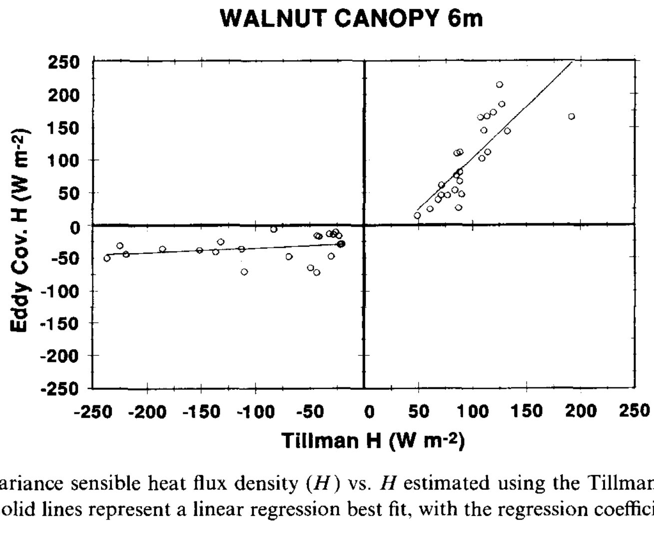


Fig. 7. Eddy covariance sensible heat flux density (H) vs. H estimated using the Tillman method for the walnut canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

error = 19 Wm^{-2} for stable conditions, and $r^2 = 0.35$, standard error = 59 Wm^{-2} for unstable conditions, both filtered data) similar to those for data screened for fetch. These results are not presented in more detail for the sake of brevity.

Tillman's method did not work well for the walnut canopy (Fig. 7 and Table 5) for stable conditions, as expected. For unstable conditions and the 6 m height, the method worked as well as the surface renewal with a similar r^2 (0.63), a slope of 1.57, and a smaller standard error of 36 W m^{-2}. The slope for the 12 m height data was closer to one (1.15). As in the case for the maize canopy, using z/L instead of $(z-d)/L$ improved the regression fit slightly ($r^2 = 0.71$), but the results are not shown in the table for the sake of brevity.

Regression of the sensible heat flux density on temperature variance alone yielded a fit better than the Tillman method for unstable conditions (Table 5). The slope of 262 W m^{-2} K^{-1} was larger than that for the maize canopy (180 W m^{-2} K^{-1}). Stable conditions resulted in a poor fit, similar to the case for the Tillman method.

5.3. The forest canopy

The forest canopy surface renewal results contrasted with those for the maize canopy (Fig. 8 and Table 6). The best results, with filtered data, were for unstable conditions (slope = 1.06, $r^2 = 0.81$, standard error = 34 Wm^{-2}). Stable conditions with filtered data resulted in greater errors than unstable conditions, but were comparable in accuracy to the case for the walnut canopy.

Unfiltered data yielded larger errors (Table 6), with the stable case showing little correlation, and the unstable case explaining 50% of the variance. The slope of the unfiltered data fit, 0.029, was less than that for the walnut canopy (0.034), which in turn was less than that for the maize canopy (0.047), representing a decreasing trend with increasing canopy height.

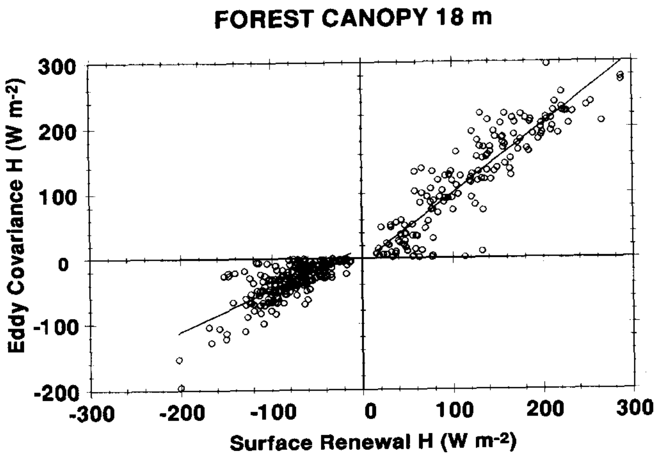


Fig. 8. Eddy covariance sensible heat flux density (H) vs. H estimated using surface renewal analysis with filtered temperature data, for the forest canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the tables.

Table 6
Regression coefficients for surface renewal and Tillman methods, forest canopy

(a) Surface renewal

Stability	Filter	r^2	Standard error ($W m^{-2}$)	a	b ($W m^{-2}$)	n
Stable	No	0.03	28	0.0015	−24.9	229
Unstable	No	0.50	54	0.029	−58.0	151
Stable	Yes	0.55	19	0.64	15.8	229
Unstable	Yes	0.81	34	1.06	4.3	151

(b) Tillman method

Stability	Height	r^2	Standard error ($W m^{-2}$)	a	b ($W m^{-2}$)	n
Stable	18 m	0.00	39	−0.079	−38.9	50
Stable	34 m	0.03	60	−0.341	−66.4	89
Unstable	18 m	0.01	118	0.12	168.9	162
Unstable	34 m	0.01	378	−0.347	290.6	94
($\|H\| > 20\ W m^{-2}$)						
Stable	18 m	0.00	26	−0.013	−57.7	48
Stable	34 m	0.03	65	0.402	−61.2	59
Unstable	18 m	0.32	52	0.611	42.6	77
Unstable	34 m	0.07	110	0.395	159.5	82

The seeming reversal of the stability conditions for the most accurate results could be an artifact of the differences of the range of sensible heat flux density magnitudes experienced over the different surfaces, although we have no convincing proof of this. The range of stable sensible heat flux densities was less for the forest than for the maize case, for example.

Tillman's method failed to produce accurate heat flux density estimates for the forest canopy (Fig. 9 and Table 6), even under unstable conditions and even when all eddy covariance sensible heat flux densities less than 20 W m^{-2} were omitted. At twice the canopy height (34 m), the fit became worse. Using z/L instead of $(z - d)/L$ did not greatly change the results.

As with the previous canopies, the variance method (Table 4) fared slightly better than the Tillman method (Table 6). For unstable conditions, the r^2 was 0.27 with a standard error of 68 W m^{-2} and a slope of 253 W m^{-2} K^{-1}. The slope is comparable with that for the other two canopies (180 W m^{-2} K^{-1} and 262 W m^{-2} K^{-1} for maize and walnut, respectively). For stable conditions, the fit was poor.

6. Summary and conclusions

Regression of sensible heat flux density obtained from the surface renewal method with unfiltered temperature data yielded reasonable fits, although a moderate amount

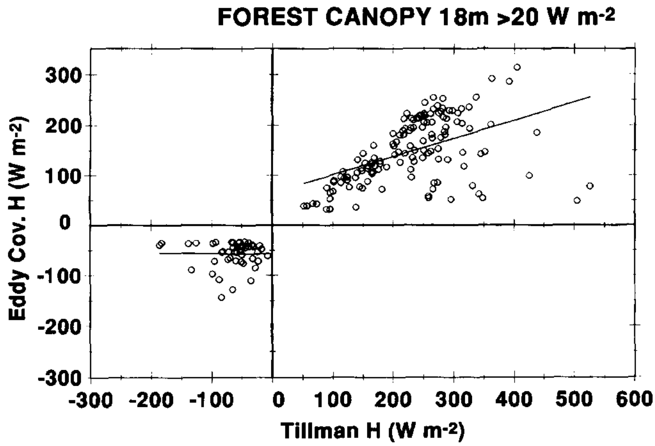


Fig. 9. Eddy covariance sensible heat flux density (H) vs. H estimated using the Tillman method for the forest canopy. Solid lines represent a linear regression best fit, with the regression coefficients given in the Tables.

of scatter is apparent. A possible trend in the slopes for unstable fits was found. For the two shorter canopies, stable conditions yielded a better fit than unstable conditions, although for the walnut data the fit for unstable data was almost equal in accuracy to the fit for stable data. The regression results for filtered data show that the standard error of the estimate for each short canopy (11–12 W m^{-2} for maize and 19 W m^{-2} for walnut) under stable conditions was within the standard error typically found in inter-instrument calibrations. Under unstable conditions, the errors were larger (17–19 W m^{-2} for maize and 45 W m^{-2} for walnut), but still comparable with the errors reported for previous work over shorter canopies (18–45 W m^{-2}) with the Tillman method (Lloyd et al., 1991) under unstable conditions. The slope of our fits changed substantially between stable and unstable conditions.

The surface renewal method seemed to decrease slightly in accuracy as height above the maize canopy increased. For the shorter canopies, there was some indication that the surface renewal method was not sensitive to inadequate fetch.

There was good agreement between the surface renewal method and eddy covariance measurements for unstable conditions, for the forest canopy. There was more error for stable conditions.

Our Tillman (1972) method results were similar to those of previous authors (Weaver, 1990; Lloyd et al., 1991) for unstable conditions for all canopies, although our regression fits tended to be somewhat worse. This could be a result of the taller canopies used in our study. The Tillman method and temperature variance methods did not work as well for the forest canopy as for the shorter canopies, lending credence to the preceding speculation. Increasing the height above the canopy did not greatly improve the Tillman method estimates, up to twice the canopy height.

The temperature variance method estimates correlated with sensible heat flux density slightly better than the Tillman method estimates, for unstable conditions. An average coefficient of 232 ± 45 W m^{-2} K^{-1}, relating the sensible heat flux density under unstable conditions to the temperature standard deviation, was found for all the canopies. Neither method accurately predicted sensible heat flux densities under stable conditions.

We postulate that the surface renewal method can be used accurately for stable conditions for canopies of 6 m high or lower, and that the Tillman or temperature variance methods could be used for unstable conditions when the surface renewal errors are greater. Calibration against eddy covariance or other methods may be needed. For the taller canopies, such as the forest canopy examined here, only the surface renewal method appeared adequate for sensible heat flux estimates, compared with the Tillman and temperature variance methods. Any scalar flux can be estimated with the methods noted above, although only sensible heat flux was tested here.

The accuracy of the surface renewal method lends support to other reports that coherent structures are responsible for more than 50% of flux exchange with plant canopies (Gao et al., 1989). Future work could include usage of structure functions (Van Atta, 1977) and wavelets (Collineau and Brunet, 1993; Qiu et al., 1995), to estimate the average scalar ramp slope and therefore the scalar flux density.

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