ESTIMATING SENSIBLE AND LATENT HEAT FLUXES OVER RICE USING SURFACE RENEWAL

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Abstract

The performance of surface renewal (SR) analysis for estimating sensible (H) and latent (λE) heat fluxes has been analysed over a sprinkler irrigated rice. Similarity principles were not fully met during the experiment and the (H+λE) measured values with the eddy covariance did not close the surface energy-balance. H and λE estimates using SR analysis were reliable and provided a reasonable energy-balance closure. The Bowen ratio was also estimated using SR analysis. Good estimates were obtained though mainly under unstable atmospheric conditions.

Keywords

Sensible heat flux, Latent heat flux, Surface energy balance, Surface renewal

1. Introduction

The search for methods for estimating sensible (H) and latent (λE) heat fluxes using low-cost, transportable and robust instrumentation constitutes a subject of interest. Surface renewal (SR) analysis for estimating scalar exchange has the advantage that only requires measurement of the scalar at a point. Therefore, SR analysis is affordable and avoids requirements such as levelling, shadowing, fetch and measurement of other meteorological variables (Paw U et al., 1995 and 2005). SR analysis has been mostly used for estimating H. Such experiments include measurements taken close to and well above different surfaces such as bare soil, homogeneous, heterogeneous, short and tall vegetation. Most of these studies have focused on analysing the performance of parameter α in Eq. (1) (Castellvi, 2004; Paw U et al., 2005). Although SR analysis is valid for any other scalars such as water vapour, little has been published about other scalars. The aim of this paper was to test the performance of two SR analysis approaches for estimating both H and λE: 1) SR analysis using the expression for parameter α proposed by Castellvi (2004); and 2) combining the surface energy balance equation and estimates of the Bowen ratio using SR analysis to avoid the dependence on parameter α.

2. Theory

Paw U et al. (2005) provides a full description on SR analysis. In SR analysis, H and λE are estimated at measurement height z by the following expressions:

$$H = (\alpha z)\rho C_p \frac{A_T}{\tau_T} \qquad \lambda E = \lambda (\alpha z) \frac{A_q}{\tau_q} \tag{1}$$

where: C_p, ρ and λ are the specific heat of air at constant pressure, air density and latent heat of vaporization, respectively. Parameter α is a factor that corrects the unequal amount of the scalar (T, air temperature; q, water vapour density) from the measurement height to the ground. For H, a summary of research carried out on parameter α can be found in Castellví (2004). A and τ are, respectively, the mean ramp amplitude and frequency for the corresponding scalars. Appendix A describes a practical method for estimating ramp dimensions and the parameter α [Eq. (A.6)], which avoids the need for calibration (Castellvi, 2004). Wind speed at a reference level is required for solving Eq. (A.6) because it depends on the friction velocity, u_*, and the stability function for the transfer of a scalar, $\phi(\zeta)$, with ζ the stability parameter defined as $\zeta=(z-d)/L_O$, where d is the zero-plane displacement and L_O is the Obukhov length. Nevertheless, cup anemometers are robust and low-cost.

According to similarity theory, the function $\phi(\zeta)$ for heat, $\phi_h(\zeta)$, and for water vapour, $\phi_q(\zeta)$, is the same. The following are expressions for $\phi(\zeta)$ [Högström, 1996] and L_O:

$$\phi(\zeta) = \begin{bmatrix} 0.95(1-11.6\zeta)^{-1/2} & -\zeta \le 2.0 \\ 1+8\zeta & 0 \le \zeta \le 0.5 \end{bmatrix} \tag{2}$$

$$L_o = -\frac{u_*^3}{\frac{k\,g}{\rho}\left(\frac{H}{T\,C_p} + 0.61\,E\right)} \tag{3}$$

where: $k\approx 0.4$, von Kármán constant; g, gravity acceleration; T, mean absolute temperature; E, water vapour flux. Combining Eqs. (1) and (A.5), the Bowen ratio (β), defined as $\beta=H/\lambda E$, can be estimated as:

$$\beta \approx \frac{\rho\,C_p}{\lambda}\left(\frac{S^3_{T(rx)}}{S^3_{q(rx)}}\right)^{1/3} \tag{4}$$

where the function $S^n(r)$ is defined in Eq. (A.1) in Appendix A. Equation (4) assumes that $(\tau_q/\tau_T)^{1/6}(r_{xq}/r_{xT})^{1/3}\approx 1$, i.e. the ramp frequency for any scalar should be similar and the 3rd order structure function for temperature and humidity approximately peak at the same time lag. When net radiation (R_n) and soil heat flux (G) are available and the simplified surface energy balance equation ($R_n-G=H+\lambda E$) is valid, H and λE can be estimated as follows:

$$H = \frac{\beta\left(R_n - G\right)}{1+\beta} \qquad \lambda E = \frac{\left(R_n - G\right)}{1+\beta} \qquad (5)$$

3. Materials

The experiment was carried out at a flat, windy and semiarid site within the Ebro River basin, Spain (41°43′ N, 0°49′ W, elevation 225 m) on days 225-226 (August 13-14) and 239 to 242 (August 27-30) of year 2002 in a plot (115 m x 100 m) of homogeneous sprinkler-irrigated rice crop (0.4 m tall), having full canopy cover. Therefore, the zero plane displacement and the aerodynamic surface roughness length, z_o, were estimated as d=0.7 h and z_o=0.12 h with h the canopy height (Brutsaert 1988). For practical purposes, the parameter γ was set to 1.1 (Appendix A). Unlike other days during the study, days 225 and 226 had calm wind conditions. A 3-D sonic anemometer CSAT3, a krypton hygrometer KH20, and a fine wire thermocouple (76 μm diameter) were set up at 1.5 m height. The three wind speed components, air temperature and humidity were recorded at 10 Hz. Half-hourly R_n and G were also measured. The upwind fetch was 75 m in the prevailing wind direction. Raw data quality control and flux corrections were made according to Paw U et al. (2000) and Mauder et al. (2004). Data gathered during dew formation and with fetch less than 75 m were removed. The analyses included 54 samples gathered under stable and 76 samples collected under unstable atmospheric conditions. The observed ζ and u_* (m s^{-1}) were, respectively, in the range; $-0.6 \leq \zeta \leq 0.56$ and $0.09 \leq u_* \leq 0.66$.

A large field of 0.35 m tall, homogeneous, and sprinkler-irrigated alfalfa was the upwind of the rice plot. Footprint analysis following Kormann and Meixner (2001) showed that more than 83 % of observed fluxes under unstable conditions came from the rice plot regardless of wind conditions. Under stable conditions, however, only 75 % and 61 % under windy and near-calm conditions, respectively, of the observed fluxes came from the rice plot. These results suggest lack of similarity (mainly for $\zeta \geq 0$), therefore, assumptions in Eqs. (A.6) and (2) may not hold. Surface-layer similarity theory assumes a perfect correlation between scalar fluctuations (Hill, 1989), which do not occur when sources (sinks) are differently distributed (McNaugthon and Laubach, 1998).

The mean correlation coefficients between air temperature and specific humidity, R_{Tq}, were 0.80 for ζ<-0.01 and -0.76 for ζ>0.01. For the remaining atmospheric conditions, absolute R_{Tq} values were small (less than 0.45). Late afternoon, negative R_{Tq} values were observed when H<0 and (R_n-G)>0. A small R_{Tq} value is a necessary condition for non-similarity but not sufficient to conclude that the stability functions $\phi_h(\zeta)$ and $\phi_q(\zeta)$ are different (McNaugthon and Laubach, 1998). Therefore, a lack of similarity may have a minor impact in Eq. (4), which assumes $\phi_h(\zeta)/\phi_q(\zeta)$=1. When upwind fetch is limited, it is possible to take measurements close to the canopy and use SR analysis. Under windy conditions, however, it may be difficult to detect well formed ramps in the scalar traces over short vegetation, because of the high absorption of momentum, unless measurements are taken at very high frequency. For sensible heat measurements, the combination of Eq. (1) and Eq. (A.6) agreed well with a sonic anemometer when measuring slightly above the adjusted surface layer (Castellvi, 2004). It was therefore decided to measure the scalar traces 1.0 m above the canopy top within the inertial sub-layer. The roughness sub-layer depth was estimated as twice the canopy height (Brutsaert, 1988).

The following sets of H and λE values were obtained for half-hour periods. A) Using the eddy covariance method (EC): 1) sensible (H_{EC}) and latent (λE_{EC}) heat fluxes and 2) sensible ($H_{BR\text{-}EC}$) and latent ($\lambda E_{BR\text{-}EC}$) heat fluxes implementing β=($H_{EC}/\lambda E_{EC}$) in Eq. (5). B) Using SR analysis: 1) sensible (H_{SR}) and latent (λE_{SR}) heat fluxes obtained from Eqs. (1) and (A.6) and 2) sensible ($H_{BR\text{-}SR}$) and latent ($\lambda E_{BR\text{-}SR}$) heat fluxes obtained combining Eqs. (4) and (5).

4. Results

The energy balance closure of the eddy covariance method and SR analysis was evaluated by simple linear regression between R_n-G (independent variable) and either H_{EC}+λE_{EC} or H_{SR}+λE_{SR} (dependent variables) and computation of root mean square error (RMSE) (Table 1). The regression slope and intercept are not easy to interpret. Beside uncertainties derived from neglected terms in the energy budget, other factors such as horizontal and vertical advection and measurement errors may play a key role. Moreover, such uncertainties are variable in time (Laubach and Teichmann, 1999). However, SR analysis provided determination coefficients (R^2) and regression slopes closer to 1.0 and lower bias and RMSE than using EC whatever the stability conditions and for the whole data set. Although not listed in Table 1, the worst performance was obtained for samples where $u_* < 0.25$ m s^{-1} (calm winds and stable conditions) for both eddy covariance and SR analysis. The values shown in Table 1 were within the range obtained in other studies where all terms in the energy budget were measured. In such experiments, that include different types of terrains, canopies and climates, an imbalance of 10 to 30% has been reported (Twine et al., 2000; Wilson et. al, 2002). A worse imbalance during nighttime and time periods with low turbulence intensity is well recognized (Wilson et al., 2002). The measurement (or estimation) of turbulent fluxes requires a certain transfer of momentum to the ground to continuously renew air parcels. Under ideal field conditions, underestimation of λE is related to the type of *EC* instrumentation (Tanner et al., 1985; Mauder et al., 2004). Therefore, H_{EC} and $\lambda E_{EC\text{-}EB}$ (computed as R_n-G-H_{EC}) were taken as references for comparison.

Table 2 gives the results of the linear fitting between: a) the independent variable $\lambda E_{EC\text{-}EB}$ and dependent variables λE_{EC}, $\lambda E_{BR\text{-}EC}$, λE_{SR} and $\lambda E_{BR\text{-}SR}$ and b) the independent variable H_{EC} and dependent variables $H_{BR\text{-}EC}$, H_{SR} and $H_{BR\text{-}SR}$. Figure 1 shows the flux estimates versus the reference values. Whatever the stability conditions, λE_{EC} and λE_{SR} were reasonable well correlated with $\lambda E_{EC\text{-}EB}$, but were slightly biased and systematically led to underestimations except for λE_{SR} under unstable conditions. The use of the Bowen ratio, $\lambda E_{BR\text{-}EC}$ and $\lambda E_{BR\text{-}SR}$, significantly improved the estimations for the unstable cases, but they performed poorly under stable conditions. Both $\lambda E_{BR\text{-}EC}$ and $\lambda E_{BR\text{-}SR}$ had some outliers that distorted the statistics [Fig. (1)]. Whatever the stability conditions, H_{SR} provided good estimates of H. Consequently, λE estimates determined as $\lambda E_{BR\text{-}}$

$_{SR}$=(R_n-G)-H_{SR} were excellent. For the entire data set, the regression slope, intercept, R^2 and RMSE were 0.93, 3.5 W m^{-2}, 0.98 and 15 W m^{-2}, respectively (not listed in Table 2). The use of the Bowen ratio, either $H_{BR\text{-}EC}$ or $H_{BR\text{-}SR}$, performed poorly under stable conditions. As with the latent heat flux measurements, some outliers distorted the statistics [Fig. (1)]. Under unstable conditions the performance was excellent. The Bowen ratio method had some outliers suggesting that smoothing routines might improve the results. The best H estimates were obtained using SR analysis.

5. Summary and concluding remarks

It is known that the closure of the surface energy budget is not guaranteed even measuring the surface fluxes using the eddy covariance method. Lack of fetch and loss of flux by convection are recognized to play a key role in the imbalance (Laubach and Teichmann, 1999; Twine et al., 2000; Wilson et al., 2002). The loss of flux by convection must be similar for samples gathered under same atmospheric conditions. Although there can be bias in eddy covariance measurements, the actual and measured turbulent fluxes must be highly correlated. Good flux estimates obtained with other approaches, therefore, must also be well correlated with eddy covariance measured fluxes. It was found that H_{SR} was highly correlated with H_{EC} under both unstable and stable conditions. Under stable conditions, the correlation coefficient between λE_{SR} and λE_{EC} was 0.77. The correlation coefficient was 0.94 under unstable conditions. A complete evaluation of the SR analysis was impossible because the references were the only reliable approximations of the actual fluxes. Surface fluxes obtained using SR analysis generally led to good energy balance closure that was superior to that obtained using the eddy covariance method. Thus, the SR technique is a good independent method for estimating surface fluxes. Moreover, H_{SR} and λE_{SR} provided a reliable energy balance partitioning according to authors' knowledge of the local climate pattern.

The use of the Bowen ratio is attractive because it forces energy balance closure. Equations (4) and (5) provided good surface fluxes estimates under unstable conditions. Although not shown, the approximation made in Eq. (4), $(\tau_q/\tau_T)^{1/6}(r_{xq}/r_{xT})^{1/3}\approx 1$, was realistic under unstable conditions but uncertain under stable conditions. The uncertainty may be due to a lack of fetch. From the equations shown in Appendix A, it is easy to demonstrate that perfect correlation (R_{Tq}=1) necessarily implies $(\tau_q/\tau_T)^{1/6}(r_{xq}/r_{xT})^{1/3}=1$. Hongyan et al. (2004) showed that ramp patterns from temperature and water vapour showed little difference in an experiment carried out over rice under unstable conditions. Therefore, $(\tau_q/\tau_T)^{1/6}(r_{xq}/r_{xT})^{1/3}\approx 1$ is a reasonable assumption at least under unstable conditions. Overall, this experiment suggests that SR analysis is feasible for estimating sensible heat flux. To our knowledge, little has been published on use of SR for latent heat flux, but seems to work well.

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APPENDIX A. Determination of the ramp parameters

Structure functions [Eq. (A.1)], Eqs. (A.1) to (A.4) from Van Atta (1977), and Eq. (A.5) from Chen et al.(1997) were used for determining ramp dimensions (amplitude and period):

$$S^n(r) = \frac{1}{m-j}\sum_{i=1+j}^{m}\left(T_i - T_{i-j}\right)^n \qquad \text{(A.1)}$$

where: m, number of data points in a 30-minute interval measured at frequency f (in Hz); n, power of the function; j, a sample lag between data points corresponding to a time lag $r=j/f$; and T_i, the ith scalar sample. An estimate of the mean value for A is determined by solving Eq. (A.2) for the real roots:

$$A^3 + pA + q = 0 \qquad \text{(A.2)}$$

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \qquad \text{(A.3)}$$

$$q = 10S^3(r) \qquad \text{(A.4)}$$

According to Chen et al. (1997), the relationship between the inverse ramp frequency (τ) and ramp amplitude is:

$$\frac{A}{\tau^{1/3}} = -\gamma\left(\frac{S^3(r_x)}{r_x}\right)^{1/3} \qquad \text{(A.5)}$$

where: r_x, time lag r that maximizes $S^3(r)/r$; and γ, factor correcting for the difference between $(A/\tau)^{1/3}$ and the maximum value of $[S^3(r)/r]^{1/3}$. For temperature, the mean parameter γ varies by less than 18% for a wide range of canopies. For bare soil and straw mulch, mean γ values varied between 1.104 and 1.175. For a fir tree forest, $\gamma \approx 1.0$.

In SR analysis, the scalar exchange is assumed through the top of the air parcel (volume control with height z), i.e, advection is neglected. Combining the one-dimension diffusion equation with SR analysis and similarity concepts, the following expression was derived when the scalar is measured in the inertial sub-layer (Castellvi, 2004):

$$\alpha = \left[\frac{k}{\pi}\frac{(z-d)}{z^2}\tau u_* \phi^{-1}(\varsigma)\right]^{1/2} \qquad \text{(A.6)}$$

Because the measurements are taken at a single level, the sign of the ramp amplitude [Eq. A.5] was used to know the atmospheric surface layer stability conditions and thus the expression for $\phi(\zeta)$ [Eq. 2]. After estimation of d and z_0, and using the wind-profile law, a typical iterative method can be implemented for solving, simultaneously, the Obukhov length [Eq. (3)], the stability parameter, the friction velocity and the sensible and latent heat flux [Eq. (1)] (Brutsaert, 1988).

FIGURE CAPTION

Figure 1. Scatter plot of flux estimates for: A) latent heat λE_{SR} [surface renewal approach using Eqs. (1) and (A.6)], $\lambda E_{BR\text{-}SR}$ [surface renewal approach combining Eqs. (4) and (5)], and $\lambda E_{BR\text{-}EC}$ [eddy covariance method implementing β=($H_{EC}/\lambda E_{EC}$) in Eq. (5)] versus the reference $\lambda E_{EC\text{-}EB}$ [forcing the

energy balance closure using the eddy covariance sensible heat, H_{EC}]. B) sensible heat H_{SR} [surface renewal approach using Eqs. (1) and (A.6)], H_{BR-SR} [surface renewal approach combining Eqs. (4) and (5)] and H_{BR-EC} [eddy covariance method implementing β=(H_{EC}/λE_{EC}) in Eq. (5)] versus the reference H_{EC}.

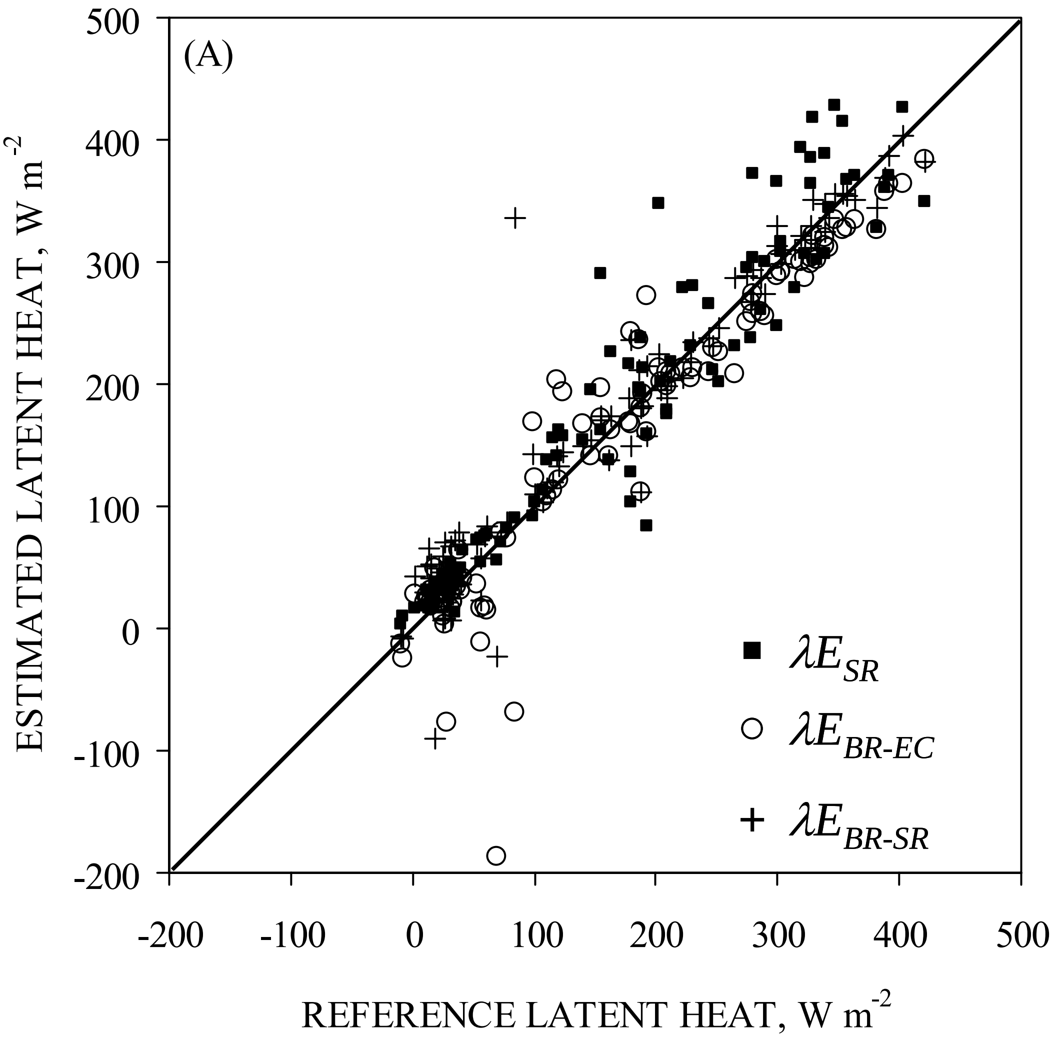
Table 1. Energy balance closure under stable and unstable atmospheric conditions determined by simple linear regression against measured net surface energy (R_n-G) values. λE_{EC} and H_{EC}, eddy covariance latent and sensible heat fluxes, respectively; λE_{SR} and H_{SR}, surface renewal [using Eqs. (1) and (A.6)] latent and sensible heat fluxes, respectively. R^2, determination coefficient. RMSE, root mean square error.

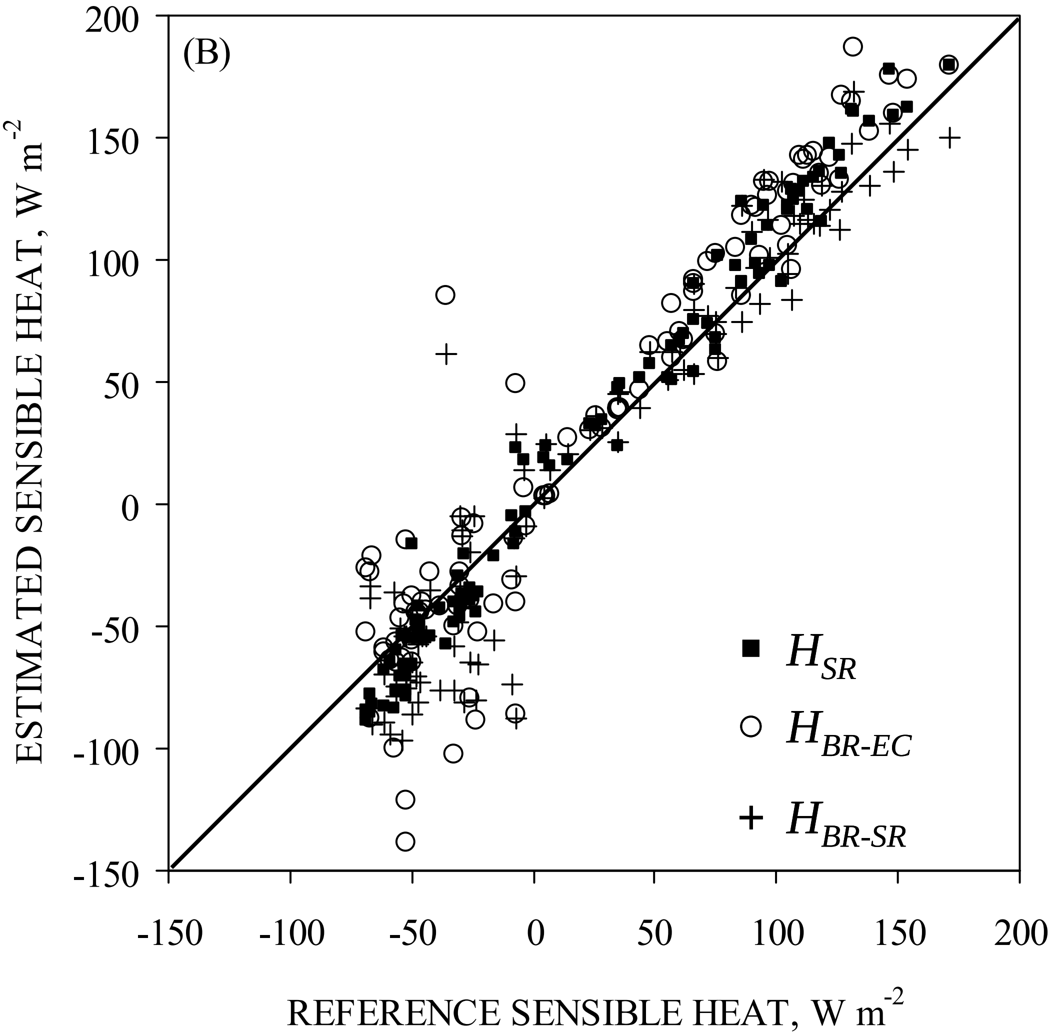
Conditions	Dependent variable	Regression slope	Intercept W m^{-2}	R^2	RMSE W m^{-2}
Stable	$\lambda E_{EC}+H_{EC}$	0.30	-11	0.68	34
	$\lambda E_{SR}+H_{SR}$	0.60	-3	0.81	23
Unstable	$\lambda E_{EC}+H_{EC}$	0.75	28.5	0.75	79
	$\lambda E_{SR}+H_{SR}$	1.05	3	0.88	54
All data	$\lambda E_{EC}+H_{EC}$	0.83	-2	0.93	64.5
	$\lambda E_{SR}+H_{SR}$	1.05	3	0.96	44.5

Table 2. Comparison of latent heat (λE) and sensible (H) fluxes obtained by the eddy covariance (λE_{EC} and H_{EC}), the Bowen ratio, β=(H_{EC}/λE_{EC}), in Eq. (5) ($\lambda E_{BR\text{-}EC}$ and $H_{BR\text{-}EC}$), surface renewal using Eqs. (1) and (A.6) (λE_{SR} and H_{SR}), and the Bowen ratio using Eqs. (4) and (5) ($\lambda E_{BR\text{-}SR}$ and $H_{BR\text{-}SR}$), against the references, H_{EC} and $\lambda E_{EC\text{-}EB}$ (determined as R_n-G-H_{EC}). R^2, determination coefficient. RMSE, root mean square error. The units for the intercept and RMSE are in W m^{-2}.

Dependent variable	Stable				Unstable				All data			
	Slope	Intercept	R^2	RMSE	Slope	Intercept	R^2	RMSE	Slope	Intercept	R^2	RMSE
λE_{EC}	0.50	13.5	0.92	23	0.65	39	0.77	65	0.61	13.5	0.92	74
$\lambda E_{BR\text{-}EC}$	1.27	-19	0.47	58	0.86	23	0.97	23.5	0.95	-3	0.90	41.5
λE_{SR}	0.67	20	0.73	23	0.93	31.5	0.77	47.5	0.985	13	0.91	39
$\lambda E_{BR\text{-}SR}$	1.28	6	0.54	51	0.96	9	0.97	15	0.94	15	0.92	35
$H_{BR\text{-}EC}$	0.16	-46	0.01	32.5	1.14	4	0.93	21	1.15	3	0.90	30
H_{SR}	1.15	-2	0.79	14	1.10	1.5	0.96	16	1.14	-2	0.98	15
$H_{BR\text{-}SR}$	0.37	-45	0.07	31	0.96	7	0.90	14	1.10	-6	0.92	25

FIGURE 1


(A)
ESTIMATED LATENT HEAT, W m-2
REFERENCE LATENT HEAT, W m-2
500
400
300
200
100
0
-100
-200
-200
-100
0
100
200
300
400
500
λE_SR
λE_BR-EC
λE_BR-SR


(B)
ESTIMATED SENSIBLE HEAT, W m-2
REFERENCE SENSIBLE HEAT, W m-2
200
150
100
50
0
-50
-100
-150
-150
-100
-50
0
50
100
150
200
H_SR
H_BR-EC
H_BR-SR