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HEIGHT EFFECT OF AIR TEMPERATURE MEASUREMENT ON SENSIBLE HEAT FLUX ESTIMATION USING FLUX VARIANCE METHOD

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Flux variance (FV) method is considered as a simple method for estimating surface fluxes of sensible and latent heat flux (H and LE, respectively). The FV method estimates sensible heat flux from high frequency temperature measurements using a fine wire thermocouple. Additional measurements of net radiation and soil heat flux, allow the derivation of latent heat flux as the residual of the energy balance closure. In this study, fine wire thermocouples were deployer over dense canopy of *Camellia sinensis*, at five measurement heights above the plant canopy, one in the roughness sublayer and four at higher levels in the inertial sublayer. In addition, reference measurements of H and LE were conducted by an Eddy Covariance (EC) system consisted of a 3D ultrasonic anemometer and an open path analyzer. The data collection was done during Sep-Nov 2018 where only the half-hourly dataset under unstable condition was investigated. Results showed better performance of the FV in the inertial sublayer as compared to the roughness sublayer. Estimations of *H* at (h_2 = 1.5m and h_3 = 2m) were in reasonable agreement with EC measurements of H, with coefficient of determination of R^2 = 0.82 and R^2 = 0.81, respectively. The estimation of latent heat flux was in good agreement with the EC method and the highest R^2= 0.89 was obtained at h2. Overall, the FV method performed well for the estimation of surface fluxes within the inertial sublayer, while the best results were obtained at a height of 2.5-3 times the canopy height.
Keywords: Flux variance, Eddy covariance, Sensible heat flux, Latent heat flux

INTRODUCTION

The plant canopy-atmospheric exchange of carbon dioxide (CO_2), energy and water vapor, is of prime importance in the study of plant biometeorology. Estimation of the surface flux of water vapor, or latent heat flux (LE) is of particular significance for crop water use and for daily to monthly crop water management (Suvočarev *et. al.,* 2014; Wilson *et. al.,* 2002). Several methods have become commonly available for estimation of evapotranspiration and the other fluxes including (net radiation (R_n), sensible heat flux (*H*), soil heat flux (G), and latent heat flux (LE)). Evapotranspiration can be estimated by systems such as EC, Bowen ratio (BR), and lysimeter. The most reliable and direct method is the EC, however, it required complex operation and is expensive to implement by farmers on a regular basis for irrigation management (Hu *et. al.,* 2018; Buttar *et. al.,* 2018; Kustas, *et. al.,* 1999). To overcome these difficulties researchers were always looking for methods, which could replace these methods for short and long periods. Several indirect methods that were developed in past few decades are Surface renewal (SR), Half-order Time Deviation (HTD) and Flux variance (FV) (Drexler *et. al.,* 2004). These methods estimate the sensible heat flux, and utilize the energy balance closure, which relates between consumed and available energy LE+H= Rn- G, to derive the latent heat flux. One of these methods, the FV, which is the focus of this study, is based on the Monin–Obukhov Similarity theory (MOST), stating that any scalar variance normalized by the scalar flux depends on atmospheric stability (ζ), attracts attention and application in the field of micrometeorology (Tillman, 1972; Wesely, 1988; Lloyd *et. al.,* 1991; De Bruin *et. al.,* 1993; Katul *et. al.,* 1995; Castellvi *et. al.,* 2005; Gao *et. al.,* 2006; Hsieh *et. al.,* 2008; Guo *et. al.,* 2009; Tanny *et. al.,* 2016). In this study, the FV method was examined for the estimation of surface fluxes over *Camellia sinensis*.

Tea (*Camellia sinensis*) plants originated in China's southwest region with warm, wet and shaded growing environment. It can usually survive at very low temperature even below -10 ^oC for short time duration. The soil with inadequate drainage capacity and with a hard layer is not suitable. The basic rainfall requirement for plant growth is about 1000~2000mm annually. These plants can be planted in plains, hilly and mountains preferably. The *Camellia sinensis* is a perennial crop with vast life span even to several decades;

it can be harvested on small scales in 3-4 years after planting (Mitscher *et. al.,* 1997).

During the past two decades, the FV method was used for the estimation of LE and *H* over different climates, surfaces, and atmospheric conditions and results were compared with the EC system, producing relativity mix results (Weaver, 1990; De Bruin and Hartogensis, 2005; Andreas *et. al.,* 1998; Asanuma and Brutsaert, 1999). In this study, the FV method was applied for an unstable condition within the range of ($0.02 \leq \zeta < 0.2$), based on the standard deviation of air temperature at high frequency (~10Hz). One main component of the FV method is similarity constant. Several studies predicted the values of the similarity constant associated with the FV method. They were evaluated from the relation of normalized standard deviation of temperature ($\sigma T/T^*$) as a function of the stability parameter (ζ) and the regression between *H* derived from the EC and FV methods (Hsieh *et. al.,* 1996; Katul and Hsieh, 1999).

The objective of this study is to evaluate the performance of the FV method for estimation of sensible and latent heat fluxes over *Camellia sinensis* with a very dense canopy. The method was examined at different measurement heights of air temperature in the roughness and inertial sub-layer. Only the data under unstable conditions were investigated by neglecting rainy period that reduced flux data suspicious.

MATERIALS AND METHODS

The campaign was carried out during Sep-Nov 2018 in a 3years mature tea orchard of about 24ha at Danyang, Jiangsu Province, P.R China (32° 1′00″N, 119°4′ 00″E, 18.5 m Above Mean Sea Level) (Figure 1). The study area is windy, dry and most frequent wind direction in winter is North-West. The plants were sprinkler irrigated with frequent application. The study area is mostly hilly terrain with an irregular surface. The tea orchard was kept weeds free throughout the growing seasons (2017-2018) (Hu *et. al.,* 2013 and Yongguang *et al.,* 2016). The climate of the study area is hot in summer but winter is very cold with some frosty nights and some snowy days, the mean temperature typically varies from -5ºC to 35ºC in winter and summer, respectively.

Data were collected during a period of 25 non-continuous days from Sept-Nov 2018. The canopy height (h) was measured every 15 days and ranged between 0.7 to 0.8m during the measurement period. The roughness sub-layer height z* was estimated as (Garratt, 1994):

$$z^* = aD + d$$

Where a is a coefficient and D the inter-row spacing (=1 m). When the crop was dense, the height of the roughness sub-layer z*. A meteorological tower (12 m high) was placed for supporting different sensors located at the south, north, east and west edges of the pole respectively. For the FV method five unshielded 50-µm, type-T fine wire thermocouples were used for measuring high frequency (~10Hz) measurement of air temperature. Sensors were placed at different heights of (1,1.5,2,2.5 and 3m) above the soil surface (Figure 1). The TCs were positioned towards the predominant wind direction (Figure 2). The measurement heights were adjusted with crop height. At each site visit, the TCs were checked for cleaning and damage, insects and cobwebs. All air temperature sensors were connected to a CR3000 data logger and were sampled at 10 HZ. The standard deviation of air temperature was calculated for each 30 mint time interval during daytime, using the high frequency temperature time series.

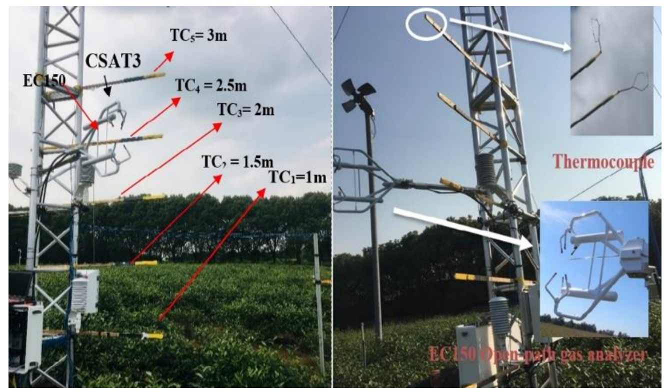


Figure 1. Experimental setup including EC and FV instrumentation.

A three-dimensional ultrasonic anemometer (model, CSAT3, Campbell Sci., USA) was used for measuring the sensible heat flux (H_{EC}) by the EC method. The sensor was placed adjacent to the thermocouples at a height in the range 1-3m above the soil surface. The sonic anemometer was positioned towards the North-West direction which was the predominant wind direction during the study period (Figure 2). The scan rate of the EC data measurement was 10Hz. All the EC flux data was processed online for every half-hour and stored in a CR3000 (Campbell Sci., USA) datalogger.

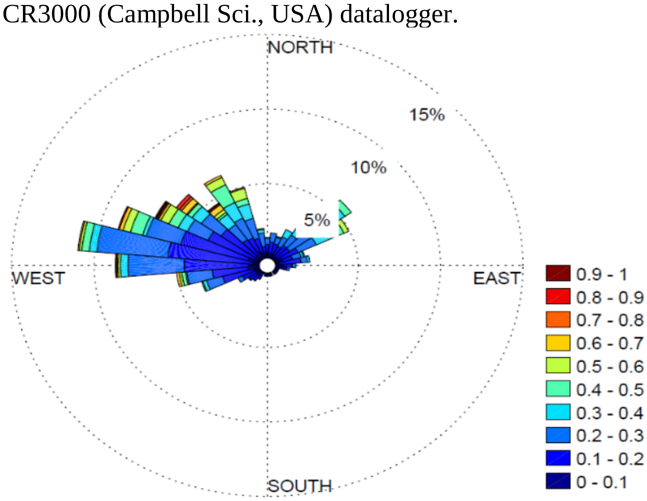


Figure 2. Wind dominant direction measured by the wind rose (NW).

Environmental conditions: During the experiment, the environmental conditions of the orchard were dry and cold in most of the season with mean windspeed of less than 1.5ms^{-1} during the study period. The average air temperature (Ta) was in the range 10-25ºC for the sonic and air temperature (Figure 4). The daily average soil temperature ranged from 9 ºC to 19.8º C. The vapor pressure deficit (VPD) ranged from 0.5-2.7 kpa (Figure 3). Mean rainfall during the study period was about 2.73 mmday^{-1}, there were some events when rainfall events were over 5.0 mmday^{-1}. The relative humidity (RH %) was high, typically exceeding 65% (Figure 5).

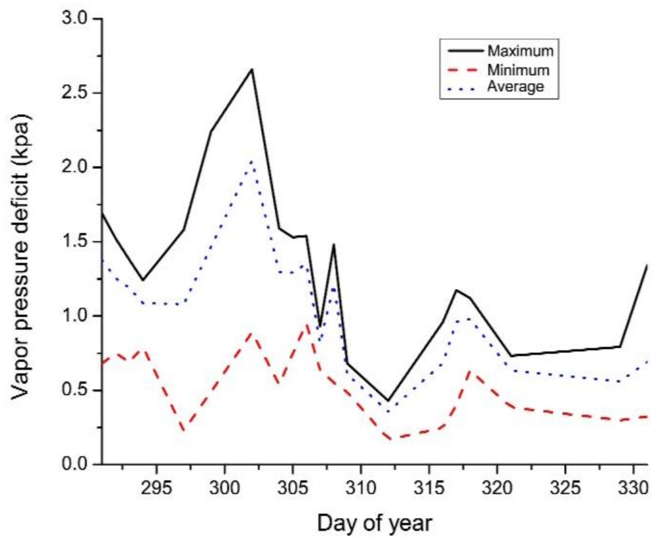


Figure 3. The maximum, mean and minimum range of vapor pressure deficit (VPD) during the study period.

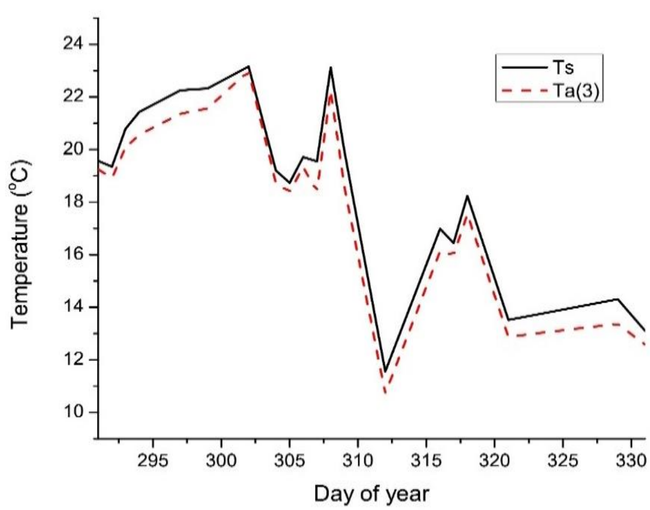


Figure 4. Comparison of the Sonic and air temperature during the study period.

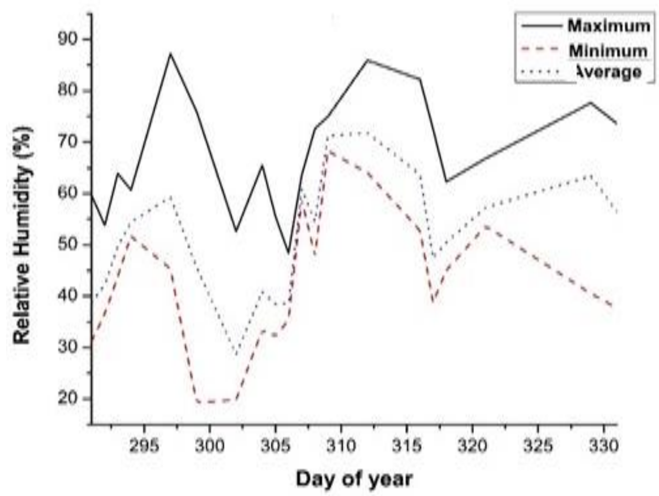


Figure 5. The variation of relative humidity (RH %) during the study period.

Overall, climatic condition was feasible for a short-term experimental study of surface fluxes estimation at different heights above plant canopy.

Eddy covariance method (EC): The EC system consisted of a 3D sonic anemometer (CSAT3, Campbell Sci., USA) and an Open-path infrared gas analyzer (EC150, Campbell Sci., USA), placed at 2.3m above the soil surface (Campbell et al., 2005). Sonic temperature,, three components of wind velocities (u, v, w), water vapors and CO_2 concentrations data were sampled at high frequency (~10Hz) and stored in a CR3000 datalogger. The raw data were processed by Easy-flux, a post-processing program by Campbell Scientific. The EC system measure H, using the following expression, $H = \rho c_p(\overline{T'w'})$, where ρ is the specific air density (kgm^{-3}), c_p is the air heat capacity (Jkg^{-1}K^{-1}) and $T'w'$ is the covariance between vertical wind speed and sonic temperature (ms^{-1}K^{-1}) (Goulden, *et. al.*, 2006). The primes over T and w denote fluctuations about their means.

Net radiation and soil heat flux

Additional measurements were done to facilitate energy balance closure. A net radiometer (CNR 4, KIPP & ZENON) was placed at 2.3m above the ground. Soil heat flux (G) was measured by three soil heat flux plates (HFP01, Hukseflux) placed 0.08 m depth in the soil. Soil temperature above thes plates, was measured by two pairs of type-E thermocouples in metal tubes placed at the soil depths of 0.02 and 0.06m, respectively. The soil water content was measured using frequency domain reflectometer inserted vertically in the soil area where the soil heat flux plates and soil thermocouples were buried. The heat stored above the plates (ΔS) was calculated as (Equation 1):

$$\Delta S = (\rho_{soil} cd_{soil} + \rho_w \theta_v c_w)\frac{\Delta z \overline{\Delta T_{soil}}}{\Delta t} \quad (1)$$

Where ρ_{soil} is the soil bulk density (kgm^{-3}), c_d the dry soil heat capacity (840 J kg^{-1}C^{-1}), ρ_w the density of water density (1000 kgm^{-3}), Θ_v is the soil water content (m^{3}m^{-3}), c_w the specific heat capacity of water (4200 Jkg^{-1}ºC^{-1}), Δz is the soil depth (m), ΔT_{soil} is the average temporal change in soil temperature above the soil heat flux plates (ºC), and Δt the time difference between each average measurement(s). The soil heat flux and temperature were measured at (10 Hz) and averaged every half-hourly period throughout the day and stored in the datalogger. G was estimated by post-processing and combining the heat flux and change in heat storage produced at each plate as (G= G′+ΔS) (Oliphant *et. al.*, 2004; Payero *et. al.*, 2005; Ortega et al., 2010). The energy balance closure was assessed by plotting the sum of turbulent fluxes (H_{EC}+LE_{EC}) against available energy (R_n–G) (Figure 6) (Wilson *et. al.*, 2002).

***Flux Variance (FV) Method*:** The FV method based on the MOST, has been the objective of many studies over the last two decades.The method has been examined at different temporatal and spatial scales and under various atmospheric conditions (Tillman, 1972). The FV method is based on high frequecny (~10Hz) measurement of air temperature by a fine-wire thermocouple (50µm, type-T, model COCO-002) and the calculation of the calculation of the temperature standard deviation. Radiation load on TC can produce small errors; though, due to very thin size of TCs junctions, these errors are assumed negligible (Wesely, 1988). For the estimation of *H* (Equation 2) is used in this stuyd (Tillman, 1972):

$$H_{FV\,c} = \rho c_p \left(\frac{\sigma_T}{C_T}\right)^{\frac{3}{2}} \left(\frac{kg(z-d)}{\overline{T}}\right)^{\frac{1}{2}} \quad (2)$$

where C_T = 0.99 is a similarity constant (Wyngaard *et. al.*, 1971), σ_T is standard deviation of air temperature (K), g is gravitational acceleration (ms^{-2}), T is the mean air temperature (K), The free convection limit under slightly unstable condition can be easily used for the estimation of *H* since it is independent of ζ and requires σ_T and T as the only input data for estimating H_{FV}. The stability parameter (ζ) is required, for identifying the unstable condition. The free convection limit for (Equation 2) is obtained by assuming the limit for $\zeta > C_2$, according to the MOST, the deviation of a scalar can be expressed as a universal function of the non-dimensional (ζ) expressed as (Equation 3) (Webb,1970):

$$\zeta = \frac{z-d}{L} \quad (3)$$

Where z = measurement height (m), and L the Obukhov length (m) measured as (Equation 4):

$$L = -\left(\frac{u_*^3 T}{kg(\overline{w'T'})}\right) \quad (4)$$

Where u_* is the friction velocity and can be calculated as (Equation 5 and 6):

$$u_* = \frac{uk}{\left(\ln\left[\frac{(z-d_{om})}{z_{om}}\right]-\psi m\right)} \quad (5)$$

or

$$u_* = \left(\langle u'w'\rangle^2 + \langle v'w'\rangle^2\right)^{\frac{1}{4}} \quad (6)$$

where u', v' and w' are three-dimensional wind speed fluctuations form their means respectively, u is the wind speed, ψ_m is the universal stability correction faction for momentum calculated as (Equation 7):

$$\psi_m = 2\,ln\left[\frac{1+x}{2}\right] + ln\left[\frac{1+x^2}{2}\right] - 2\,arctan(x) + \frac{\pi}{2} \quad (7)$$

Where $x = [1-16\zeta]^{\frac{1}{4}}$ (8)

Performance evaluation: In order to evaluate the performance of the FV method, a regression of estimations of the FV agains the measurements of the EC method was constructed for each measurement height, and following statistical analyses was performed in Microsoft Office Excel for each height separately: (a) Coefficient of dtermination (R^2), (b) the root mean square error (RMSE) (Equation 9), (c) Relative error (RE) (Equation 10)(Mahrt, 1998). The RMSE was computed using the following expression (Willmott, 1982):

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n}(y_i-x_i)}{n_o}\right]^{0.5} \quad (9)$$

where n_o is the number of 30-min periods. Finally, the relative error (RE) was computed as:

$$\mathrm{RE} = 100\,\frac{\mathrm{RMSE}}{(ymin_{max})} \quad (10)$$

where y_{max} and y_{min} are the maximum and minimum values for each regression values.

RESULTS AND DISCUSSION

***EC measurements*:** The reliability of the EC measurements of sensible and latent heat fluxes, is commonly assessed by the energy balance closure analysis. A linear regression between the consumed energy LE + H, and available energy loss (R_n-G) is shown in (Figure 6). The overall dataset was near to the line 1:1 representing the acceptance of the energy balance closure with a slop of 0.55. The applicability of the EC was proved with the good correlation coefficient (R^2= 0.83).

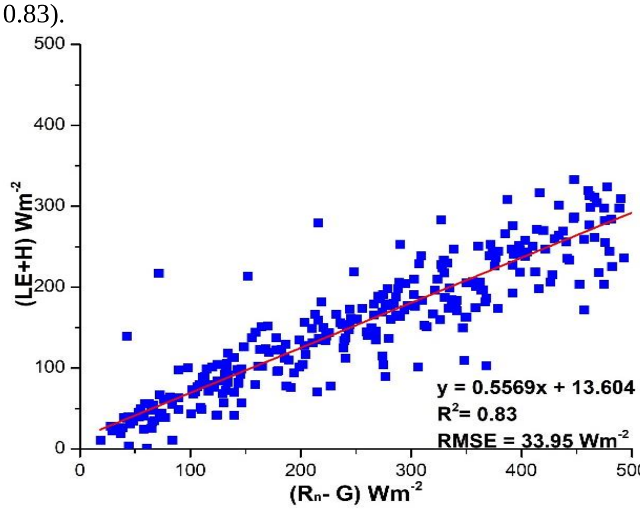
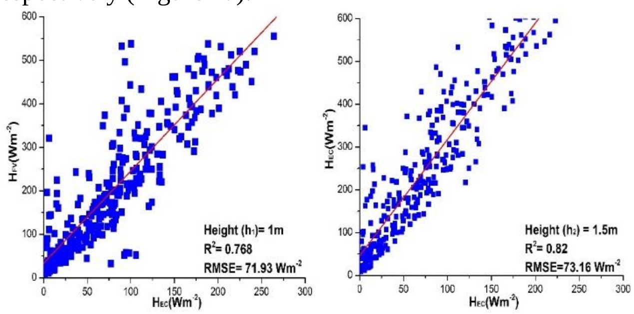


Figure 6. Linear correlation between the energy loss and surface energy.

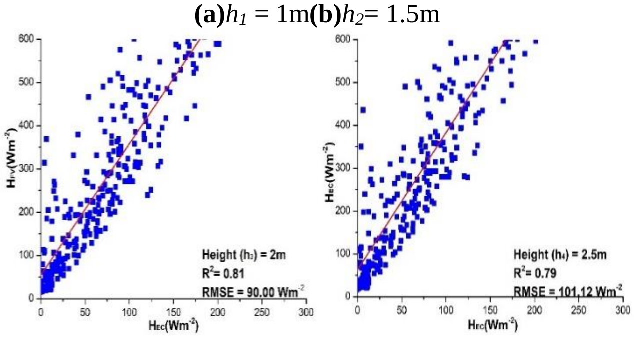
These results were in good agreement with some previous studies in different plants and orchards (Laubach, and Teichmann, 1999; Kordova *et. al.*, 1999; Testi *et. al.*, 2004). Thus, the measurement of the EC was used for analyzing the performance of the FV method for the whole experiment.

***Sensible heat flux (H_{FV})*:**

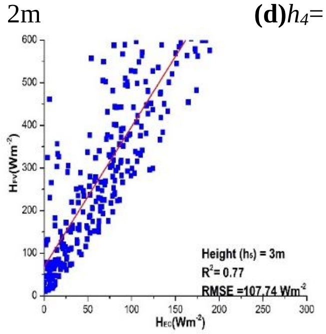
For the estimations within the roughness and inertial sublayers, the free convection H_{FV} was calculated using (Equation 2), for each height separately. The estimations at heights h_2 and h_3 were in reasonable agreement with the measurement of H_{EC} (Figures. 7b, c) with high (correlation coefficient, R^2). The estimation at the first measurement height (h_1) within the roughness sublayer was high as compared to the measurements of the H_{EC} at midday when the unstable condition for the FV method was well achieved. The results showed the coefficient of determination (R^2= 0.76), and the RMSE and RE were 71.93 Wm^{-2} and 21.56 Wm^{-2}, respectively (Figure 7a).



(a)h_1 = 1m**(b)**h_2= 1.5m



(c)h_3= 2m **(d)**h_4= 2.5m



(e) h_5= 3m

Figure 7. Comparison of H_{EC} and H_{FV} for half hourly dataset at five heights (*a*)(*b*)(*c*)(*d*) and (*e*) during (Sep-Nov 2018).

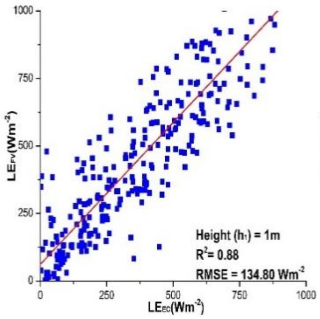
The sensible heat flux estimated at (h_2) was in good agreement with the measured of H_{EC}, although the estimation of the H_{FV} was higher than that of H_{EC} when the H_{FV} exceed ~200Wm^{-2} (Figure. 7b). Overall estimation was in good agreement with the measurement of the EC method, and it was confirmed by strong correlation (~R^2= 0.82, see Table 2), the RMSE and RE were 73.16 Wm^{-2} and 11.02 Wm^{-2}, respectively. The ability of the FV method was best confined in the mid-day hours because in these hours the conditions are most likely to be in unstable, which best defines the applicability of the FV method. The estimation of H_{FV} at the h_3 was plotted for liner correlation with the EC and produced reasonable results (~R^2 = 0.81) (Figure. 7c). The estimation was in high correlation with the measurement of the EC system when the estimation values were less than ~300Wm^{-2}, with the RMSE and RE as 90.00 Wm^{-2} and 11.89 Wm^{-2}, respectively. The performance of the estimated H_{FV} was then compared at the height (h_4) within the inertial sublayer, the estimated values of the H_{FV} were high as compared to the H_{EC} due to high deviation produced in the measured air temperature at high frequency with R^2 = 0.79, the RMSE and RE were 101.12 Wm^{-2} and 11.88 Wm^{-2}, respectively (Figure. 7d).

Table 2. Statistics of half-hourly H_{FV} estimates at all measurement heights, vs H_{EC}.

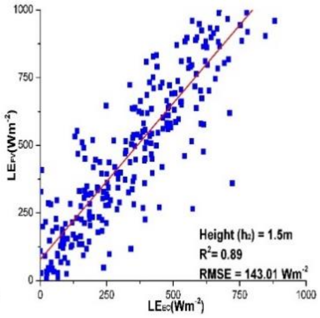
Statistics	H_{FV}				
	h_1	h_2	h_3	h_4	h_5
R^2	0.76	0.82	0.81	0.79	0.78
RMSE (Wm^{-2})	71.93	73.16	90.00	101.12	107.74
RE (Wm^{-2})	21.57	11.02	11.89	11.88	11.65
n	291	289	294	291	293

The estimated values of H_{FV} at the very last measurement height (h_5) were compared with the H_{EC} with low correlation coefficient as compared to the h_2 and h_3 as R^2= 0.78, with RMSE and RE of 107.74 Wm^{-2} and 11.65 Wm^{-2}, respectively (Figure. 7e). It was observed that the RMSE measurements increased with the increase of measurement height. The maximum RMSE value obtained was 107.74 Wm^{-2} at last height of 3m above the soil surface. The lower values of RMSE at canopy height cannot be attributed to improved performance of the FV method (Castellvi *et. al.*, 2005). The overall performance of the FV method was better in the inertial sublayer as compared to the roughness sublayer and proved the fact that the MOST is more valid in the inertial sublayer (Kaimal *et. al.*, 1994).

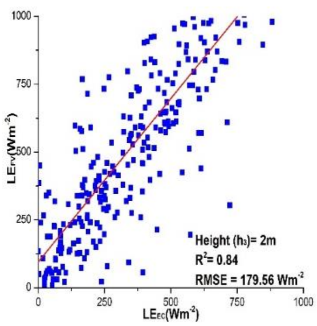
***Latent heat flux (LE_{FV})*:** The latent heat flux (LE_{FV}) was extracted from the energy balance equation (LE= R_n-G-H) for every 30-mint dataset (Thom, 1975). Half-hourly datasets of the estimations of LE_{FV} and LE_{EC} were plotted and analysed at five different height ranging from 1 to 3 m respectively (Figure. 08 a, b, c, and e). Only the positive LE estimates under the unstable condition during the daytime were investigated. All the estimations were compared separately at each height including roughness sublayer and inertial sublayer (Figure. 8). The estimation of LE_{FV} at h_1 was reasonable with the measurement of LE_{EC} with RMSE =134.80 Wm^{-2} and R^2 = 0.87. While the estimations at h_2 and h_3, best described the measurement of the EC which was proved with a strong coefficient of correlation (R^2= 0.89 and 0.84 respectively).



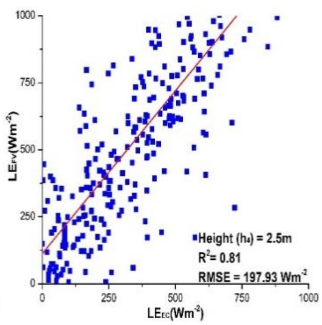
(a)h_1 = 1m



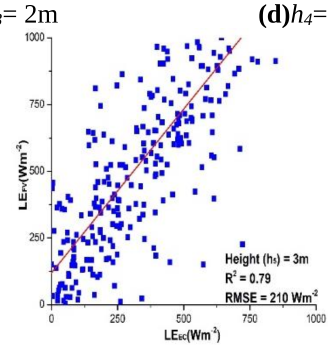
(b)h_2= 1.5m



(c)h_3= 2m



(d)h_4= 2.5m



(e) h_5= 3m

Figure 8. Comparison of LE_{EC} and LE_{FV} for half hourly dataset at five heights (*a*)(*b*)(*c*)(*d*) and (*e*) during (Sep-Nov 2018).

Table 2. Statistical variation as different positions between LE_{FV} and LE_{EC}.

Statistics	LE_{FV}				
	h_1	h_2	h_3	h_4	h_5
R^2	0.87	0.88	0.84	0.81	0.79
RMSE (Wm^{-2})	134.80	143.59	179.56	197.93	210.00
RE (Wm^{-2})	5.79	5.86	7.02	7.78	8.20
n	291	289	294	291	293

The estimations at h_4 and h_5 were RMSE and RE as 197.93Wm^{-2} and 8.20Wm^{-2} respectively. It was observed that the values of RMSE were increased with the increase in the measurement height. Mostly, The FV method estimated better the fluxes in the inertial sublayer as compared to the roughness sublayer, as discussed earlier.

***Conclusion*:** Sensible heat flux estimation can be used for ET estimated through the energy balance closure. In FV technique, estimation of sensible heat flux is based on air temperature measurements. In this study the effect of different measurement heights of air temperature on the estimation of *H* was analyzed. The surface flux estimations at h_2 and h_3, showed the best performance of the FV method within the inertial sublayer. FV performance in the roughness sub-layer was somewhat lower. In conclusion, the FV method can provide accurate and reliable surface fluxes estimates exempt from calibration in the inertial sublayer if measurements of air temperature are taken well above at (2.5-3) times of the plant canopy height. Hence, low-cost and simple temperature sensors could be used effectively for the application of FV method. This simple method can be used by the growers for day-to-day estimates of latent heat flux as an aid in irrigation management.

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