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Assessment of large aperture scintillometry for large-area surface energy fluxes over an irrigated cropland in north India

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Amount of available net energy and its partitioning into sensible, latent and soil heat fluxes over an agricultural landscape are critical to improve estimation of evapotranspiration and modelling parse (ecosystem modelling, hydrological and meteorological modelling). Scintillometry is a peculiar and robust methodology to provide structure parameter of refractive index and energy balance. Scintillometer has proven for assessment of sensible and latent heat flux, which is based on the principle of Monin–Obukhov similarity theory. Scintillometer has been installed in the agricultural experimental farm of ICAR-Indian Agricultural Research Institute, New Delhi, with a spatial covering path length of 990 m of irrigated and cultivable agricultural landscape. This paper discusses the patterns of energy flux as diurnal and seasonal basis at scintillometer path which was mainly covered by maize in Kharif and wheat in Rabi season during a crop growing seasons of 2014–2015. The biophysical parameters (leaf area, soil moisture, crop height) were recorded at a temporal resolution of fortnight basis along the path length at usual sampling distance. The Bowen ratio value for both Kharif and Rabi season was 0.76 and 0.88, respectively by scintillometer. Leaf area index had a significantly positive correlation with latent heat flux ($R^2 = 0.80$) while a significantly negative correlation with sensible heat flux ($R^2 = -0.79$). Soil moisture had a significant negative correlation with sensible heat flux ($R^2 = -0.68$). The average evapotranspiration from crop land was 1.58 mm d^{-1} and total evapotranspiration was 543 mm over the 12 months study period. This study defines that large aperture scintillometer is robust instrument which can evaluate energy flux over a large area with a long term series time domain. Moreover, further studied should be conducted to use in crop simulation modelling, developing of new model with calibration and validation of remote sensing energy balance algorithm, etc.

Keywords. Scintillometry; sensible heat flux; latent heat flux; Bowen ratio; evapotranspiration.

1. Introduction

Net available energy is the sum of energy partitioned into atmospheric and surface heat fluxes. It acts as a main driving force for exchanges of mass, heat and momentum between the surface and atmosphere, and thereby controls energy and water balance at the surface. Quantification of net available energy and associated fluxes is therefore vital in understanding the behaviour of ecosystem-scale exchange processes such as evapotranspiration and hitherto, it is crucial to evaluate spatially representative surface energy balance over an agricultural landscape for more accurate assessment of crop evapotranspiration (ET_c). The quantification of ET_c is vital to the hydrological modelling, irrigation scheduling and water allocation due to its large share of the water budget which is typically composed of ET_c in arid regions (Baumgartner and Reichel 1975). However, ET_c is still equivocal due to its dependency on type of vegetation, crop growth stage and soil–water–climatic conditions (Burman and Pochop 1994).

Some of the functional energy balance methods such as Bowen ratio energy balance (BREB) and Eddy covariance (EC) have been widely used in deriving surface energy fluxes (H and LE balance components), evapotranspiration and validating remote sensing-based ET algorithms. The BREB method has shown effectiveness for ET estimation in non-advective periods but it seems to be non-reliable during advective periods (Blad and Rosenberg 1974). The eddy covariance is a direct and the most accurate means of measuring mass and energy fluxes but such measurements are only representative of relatively small areas (few hundred metres). Additionally, the EC technique subject to limitation of energy balance closure due to small areal coverage, shows higher sensitivity for small eddies and needs variety of corrections to obtain final output of fluxes (Leuning and King 1992; Leuning and Judd 1996; Massman and Clement 2004; Ibrom *et al.* 2007; Massman and Ibrom 2008; Clement *et al.* 2009; Haslwanter *et al.* 2009). These limiting factors make EC method a quite complex and arduous for operational applications.

The latest technique of large aperture scintillometry (LAS) has emerged as the best alternative to measure path-averaged sensible heat flux (H) and atmospheric refractive index at a much larger scale of 250–4500 m (Meijninger and De Bruin 2000; Beyrich *et al.* 2002) and thus provided measurements over heterogeneous areas covering agricultural land, forest, water bodies, river basin and bare soil (De Bruin *et al.* 1995; McAneny *et al.* 1995; Meijninger *et al.* 2002; Meijninger 2003; Schuttemeyer 2005; Hoedjes *et al.* 2007; Guyot *et al.* 2009; Kleissl *et al.* 2009). Among all above, the use of LAS has proven to be a more reliable and accurate method for assessing surface energy fluxes in a variety of terrain, offering numerous benefits over the more traditional EC (Wesely 1976; Hill *et al.* 1992; Green *et al.* 1994; De Bruin *et al.* 1995; Meijninger and De Bruin 2000; Meijninger *et al.* 2002). The performance of LAS has been already examined at numerous land cover sites: vineyard (De Bruin *et al.* 1995), flat pastoral surfaces (McAneny *et al.* 1995), a rangeland site (Hartogensis *et al.* 2003), agricultural fields in humid regions (De Bruin *et al.* 1995; Cain *et al.* 2001; Meijninger *et al.* 2002; Beyrich *et al.* 2002; Kleissl *et al.* 2009) and complex terrain (Chehbouni *et al.* 2000). All these studies have reported improved accuracy of surface heat fluxes and were conclusive of superiority of LAS among all others.

The LAS measures the sensible heat flux which is the most difficult to measure at field level because of atmospheric instability with fraction of time. The measurement of net radiation, soil heat flux using net radiometer and soil heat flux plate, respectively and synchronized with scintillometry in data logger are quite necessary actions to be done. Thus, basic surface energy balance equation has to be incorporated and estimate the latent heat flux and crop evapotranspiration. LAS carries important advantage of providing areal averaged surface fluxes, which can be used for calibration and validation of remote sensing energy balance algorithm (SEBAL, Bastiaanssen *et al.* 1998; METRIC, Allen *et al.* 2007; Anderson *et al.* 2008; Chehbouni *et al.* 2008; Tang *et al.* 2011).

In view of the unique importance of LAS to capture surface fluxes over large foot-print area, the present study explores the utility of LAS for the estimation of areal-averaged surface energy balance and evapotranspiration over agricultural landscape and generate surface fluxes at comparable resolution to ET products from coarse resolution satellite data.

2. Materials and methods

2.1 *Study area*

This experimental study was carried out at the agricultural research farm of ICAR-Indian Agricultural Research Institute, New Delhi, India with geographic location as 28.63°N, 77.15°E and an elevation of 220 m above sea level. The climate is in between sub-tropical and semi-arid. June–September is the monsoon period during which 500 mm of rainfall is received. During winter, a small amount of rainfall (about 63 mm) is received. At IARI, a large aperture scintillometer (LAS, Kipp & Zonen Inc.) installed with a spatial coverage of

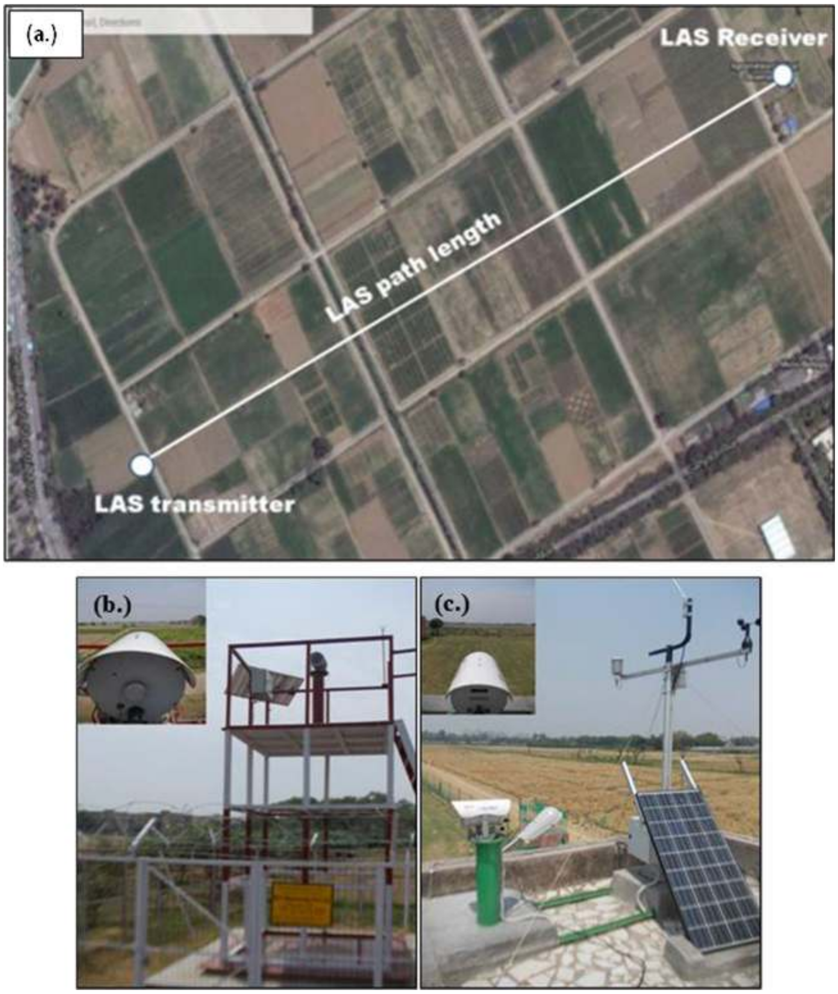

Figure 1. LAS experimental setup at IARI Research Farm. (**a**) LAS path footprint overlaid on satellite image, (**b**) LAS transmitter, and (**c**) LAS receiver.

990 m at a height of 4.5 m above field in northeast–southwest. It has transmitter, receiver and data logger (figure 1). The LAS was augmented with an automatic weather station (AWS) with sensors of net radiometer, anemometer (two levels), humidity and temperature probes (two heights) and soil heat flux plate at 10 cm depth. The frequency of data observation by LAS and AWS was set at 5 min. Estimation of surface energy flux was dominated by central zone of the path length and it was mainly persisted by maize crop in Kharif season and wheat crop in Rabi season in 2014–2015, respectively.

2.2 *Large aperture scintillometry (LAS)*

The design of scintillometer was made by Ochs and Wilson (1993) which is further modified at Wageningen University, Netherlands with improved electronics. The LAS is based on Monin–Obukhov similarity theory to derive iteratively sensible heat flux from the LAS raw measurement and support meteorological and vegetation height data (Tang *et al.* 2011). A large aperture scintillometer (LAS, Kipp & Zonen Inc.) that has transmitter, receiver and built-in data logger is further utilized to record the logarithm of the structure parameter of the refractive index of air with a base of 10 (UCn^2), the signal strength and the variance of UCn^2 every 5 min. The transmitter emits electromagnetic radiation at a wavelength λ (840–880 nm) over a known path length to the receiver, where the fluctuations of the light intensity are recorded. The turbulent intensity of the refractive index of air can be defined as refractive index structure parameter (C_n^2) which is calculated as (Meijninger and De Bruin 2000):

$$C_n^2 = \frac{\overline{n\,(r_1^2) - n\,(r_2^2)}}{r_{12}^{2/3}}, \tag{1}$$

where $n(r)$ is the refraction index at location r and the distance r_{12} lies in between the so-called inner scale of turbulence and the outer scale. C_n^2 value is directly related to the structure parameter of temperature C_T^2; humidity C_q^2 and the covariance term C_{T_q} as shown in the equation below (Kohsiek 1982; Hill *et al.* 1992):

$$C_n^2 = \frac{A_T^2}{T^2} C_T^2 + \frac{A_T A_q}{T_q} C_{T_q} + \frac{A_q^2}{q^2} C_q^2. \qquad (2)$$

The first term, containing C_T^2 is much greater than the other two terms. Assuming that temperature and humidity are perfectly correlated, equation (2) can be written as (Wesely 1976):

$$C_T^2 = C_n^2 \left(\frac{T^2}{-A_T P} \right)^2 \left(1 + \frac{0.03}{\beta} \right)^{-2}, \qquad (3)$$

where Bowen ratio (β) is assumed ≈ 0.5 for irrigated agroecosystem for estimation of structure parameter of temperature. Under the assumption of local free convection conditions, the sensible heat flux can be calculated from C_T^2 as:

$$H = \rho C_p b \left(z - d \right) \left(\frac{g}{T} \right)^{1/2} \left(C_T^2 \right)^{3/4}, \qquad (4)$$

where $b = 0.57$ is an empirical constant (De Bruin *et al.* 1995), z is the height, d the displacement height, C_p the specific heat of air at constant pressure and g is gravitational constant. In this study, the values for the displacement height (d) and roughness length (z_0) were counted using the thumb rule relationship with the vegetation height (h): $d = 0.67h$ (m) and $z_0 = 0.1h$ (m).

2.3 *Surface energy balance equation*

The surface energy balance equation is written as:

$$R_n = H + LE + G, \qquad (5)$$

where R_n is the net radiation flux; H is the sensible heat flux, LE is the latent heat flux and G is the soil/ground heat flux. The units of energy balance terms are Wm^{-2}. R_n and G were measured by net radiometer and ground heat flux plate, respectively at 5 min interval. Therefore, combining LAS with AWS measurements in EVATION$^{\mathrm{TM}}$ software (Kipp & Zonen), the 5-min fluxes of H and LE were computed in $\mathrm{MJm}^{-2}\mathrm{d}^{-1}$. Using H and LE daily integrated fluxes, daily values of evaporative fraction (EF) were computed as below and studied for their seasonal pattern.

$$EF = \frac{LE}{R_n - G}. \qquad (6)$$

2.4 *Micrometeorological sensors and measurements*

Large aperture scintillometer comprising other automatic meteorological sensors were installed at IARI, New Delhi (table 1). Meteorological parameters (air temperature, relative humidity, wind speed, wind direction, net radiation) were observed at automatic weather station (AWS) at 5-min interval in between the study period. Seasonal variation in relative humidity and wind speed during crop growing seasons are illustrated in figure 2.

2.5 *In-situ field measurements*

The crop parameters such as leaf area index (LAI), height, phenological stages and soil moisture at 12.5 cm depth were measured periodically at fortnightly interval over the fields along the 990 m path length of LAS. More than 70 readings were taken at a time period in LAS path length for obtaining site representative value of biophysical parameters (crop and soil). Weighted average was done for getting a single value on the basis of area covered by one type of crop. Seasonal evolution of LAI and volumetric moisture content in percentage (VMC) is depicted in figure 3.

3. Results

3.1 *Diurnal pattern of measured energy fluxes*

Continuous measurements of energy fluxes from combining LAS and AWS were analysed at 5 min interval and averaged to hourly basis for depicting diurnal behaviour of R_n, H, LE and G (figure 4). Fluxes of H, LE and G followed similar pattern diurnally as that of R_n across all months during 2014–2015 crop growing season. According to the sign convention followed, all the radiative fluxes directed towards the surface are positive and *vice-versa*, whereas non-radiative fluxes directed away from the surface are positive and *vice-versa*. Therefore, fluxes were positive during day time and negative during night time. The peak values were occurred as 490.5, 231.7, 91.9 and 297.3 Wm^{-2} for R_n, H, G and LE in April, May, and August,

Table 1. *Sensors along with make and measurable parameters installed at site.*

Type of observations	Parameter	Sensor	Make/Model
Surface energy	Sensible heat flux	Large aperture scintillometer	Kipp & Zonen: MK- II
Radiation	Netradiation	Net radiometer	Kipp & Zonen: NR-LITE
	Incomingglobalradiation	Pyranometer	Kipp & Zonen: CMP3
Multi-level meteorological parameters (2 level)	Windspeed	Anemometer	Gill 3 cup: 12102
	Relativehumidity	Humidity probe	Campbell Scientific: CS 215
	Airtemperature	Temperature probe	Campbell Scientific: CS 215
Biometric	Leaf area index	Plant canopy analyser	LI-COR: LAI 2000
Soil	Soilmoisture	Time domain reflectometer	Spectrum Tech.: FieldScout 300
	Groundheatflux	Soil heat flux plate	Hukseflux: HFP∅1

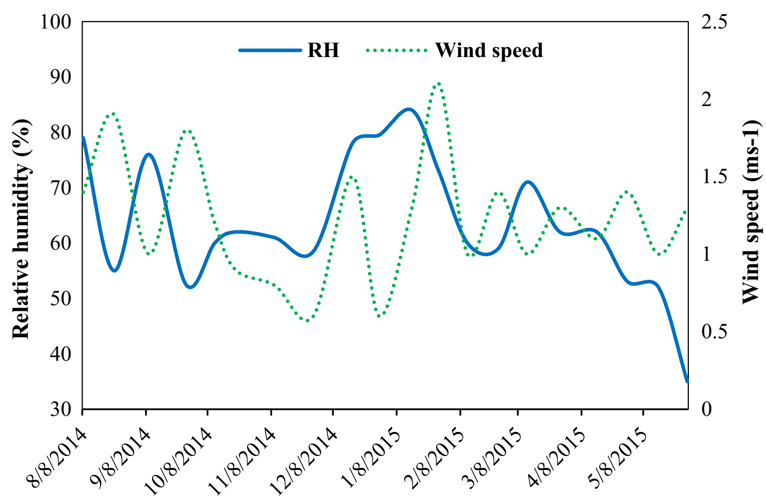

Figure 2. Seasonal variation in relative humidity and wind speed in the study period.

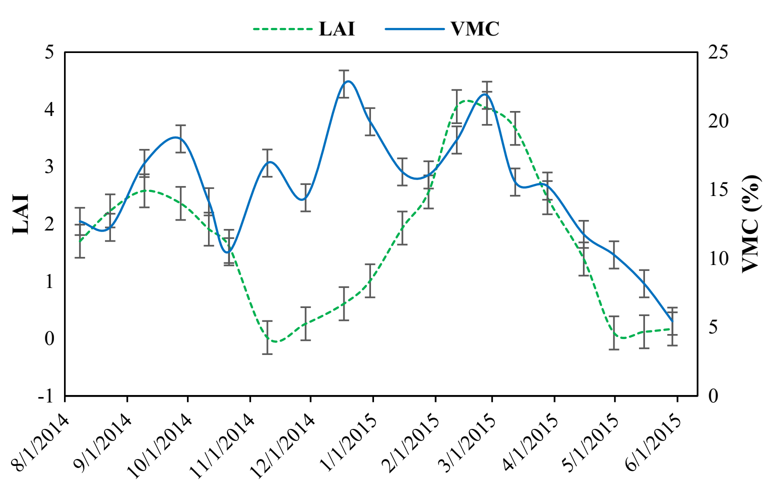

Figure 3. Seasonal variation in weighted LAI and VMC (%) with SE bar.

respectively. The figure depicts that the R_n was almost equally partitioned into H and LE in June. However, LE remained higher than H until September due to favourable soil moisture conditions and incremental leaf biomass and crop growth following the onset of monsoon. As crop advances

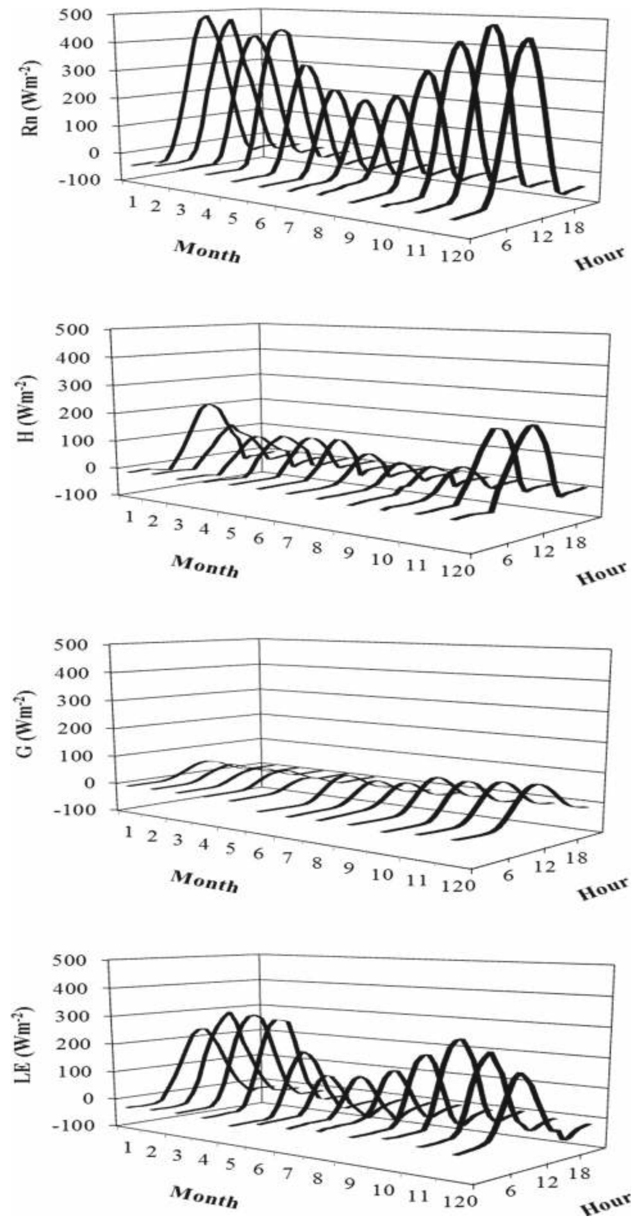

Figure 4. Monthly diurnal pattern of surface energy fluxes from June 2014 to May 2015.

to maturity and monsoon withdrawal took place by October and the trend reversed with more energy, partitioned into H. A period of in between two crop seasons, H was higher as compared to LE due to fallow period and after slow crop growth from November to mid-December. With active crop growth and ample of availability of water during different crop growth stages, LE became much higher than H from mid-December to March. As the crop maturity phase came, H increased and LE decreased in April and after that, H was much higher than LE as fallow period came in May month.

Soil heat flux has expressed a specific behaviour during different seasons. Soil acts as a sink in summer whereas act as a source in winter. Average G value was near to approx. 10% of average monthly R_n for all the months of year except November, December and January. The monthly G/R_n ratios were –18.93, –50.64 and –18.45 for November, December and January, respectively. Here, the negative sign shows that soil acts as a source of energy for surroundings. In winter months, solar radiation is very less and foggy weather also occurred, therefore G/R_n value was quite high. That is why G becomes crucial parameter of surface energy balance study in diurnal as well as in seasonal basis.

3.2 *Seasonal pattern of measured energy fluxes*

It is also imperative to understand variation in the fluxes over a season to discern seasonality response to biophysical and environmental factors. Daily fluxes of R_n, H, G and LE are plotted graphically and illustrated in figure 5. Daily net radiation stands at relatively higher value, i.e., around $9.55\,\mathrm{MJm^{-2}d^{-1}}$ during June–September, after that it declined from October onwards and remained $<5\,\mathrm{MJm^{-2}d^{-1}}$ till February. Then again it has increased up to $9.04\,\mathrm{MJm^{-2}d^{-1}}$ in summer (April and May). With seasonal variation, the least value of daily R_n ($1.50\,\mathrm{MJm^{-2}d^{-1}}$) was noticed in December month. These variations are governed due to Earth–Sun distance and inclination of the solar radiation regarding horizontal earth surface. The G/R_n ratio was found close to 7% on annual basis. H and LE define the atmospheric turbulence fluxes which are more relevant to crop biometric parameters and soil moisture availability. R_n was partitioned in between H and LE with progress in crop phenological stages and crop seasons. H was generally higher than LE due to more fallow land than crop acreage in dry period of June, while H remained almost one-fourth of LE ($1.56\,\mathrm{MJm^{-2}d^{-1}}$ as compared to $6.82\,\mathrm{MJm^{-2}d^{-1}}$) in rainy season (mid-July to mid-September). At crop maturity and harvesting stages, the H started increasing and LE started decreasing during mid-September to the end of October. At adjoining period of Kharif and Rabi (November), H was five times higher than LE ($2.23\,\mathrm{MJm^{-2}d^{-1}}$ as compared to $0.40\,\mathrm{MJm^{-2}d^{-1}}$) due to fallow period and more conversion of energy of R_n into H. After that LE was increased day-by-day as compared to H ($3.53\,\mathrm{MJm^{-2}d^{-1}}$ as compared to $1.59\,\mathrm{MJm^{-2}d^{-1}}$) due to regular crop growth till March. As the crop

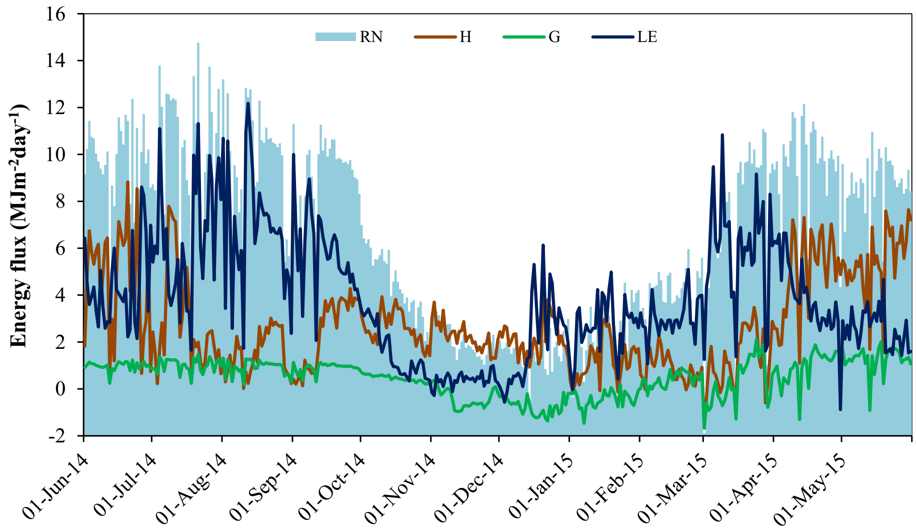

Figure 5. Seasonal pattern of energy flux (R_n, G, H, LE) at the LAS path length by scintillometer.

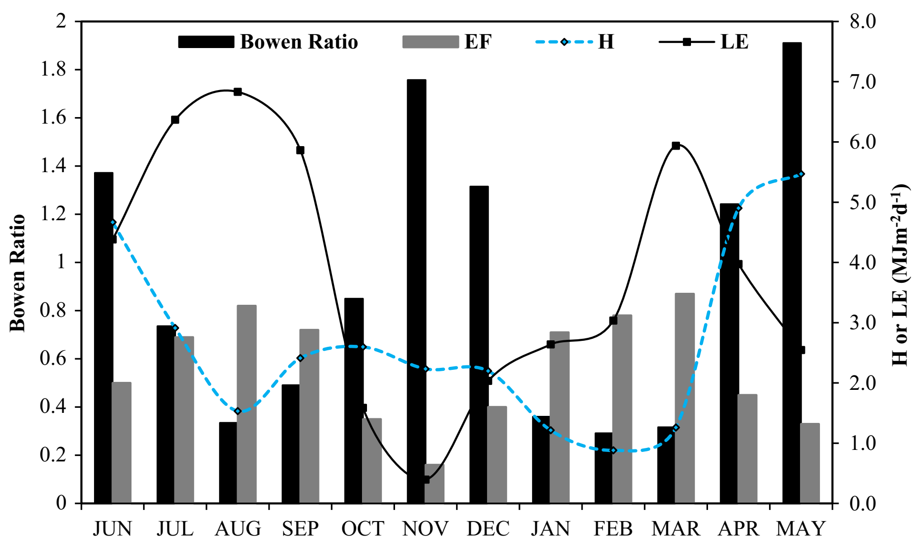

Figure 6. Monthly Bowen ratio and EF trend with H and LE.

maturity phase came, H increased sharply. Then, H was more than double of LE in May due to fallow land and unavailability of soil moisture.

3.3 *Seasonal pattern of Bowen ratio with H and LE*

Bowen ratio (B) is the proportion of H and LE. Scintillometer measured atmospheric turbulence fluxes and Bowen ratio itself. Monthly B value varied from 0.33 to 1.37 for Kharif season and 0.29 to 1.75 for Rabi season (figure 6). This figure showed that in June, H was higher than LE, so B value was more than one. As the onset of monsoon occurred and crop growth was predominated, LE was step-up and H was step-down, simultaneously B value was decreased. As soon as crop reached the maturity stage, B was increased same as in fallow period due to lower LE. In Rabi crop, same pattern had accompanied as in Kharif crop. Minimum Bowen ratio value occurred at the time of maximum crop growth and *vice-versa*. Bowen ratio had a highly significant negative correlation with LAI value ($R^2 = 0.83$, $p = 0.0002$), which shows that LAI plays a key role in the estimation of Bowen ratio (figure 7). In fallow period, B value was always more than one because H was much higher than LE as no vegetation occurrence is directly responsible for LE.

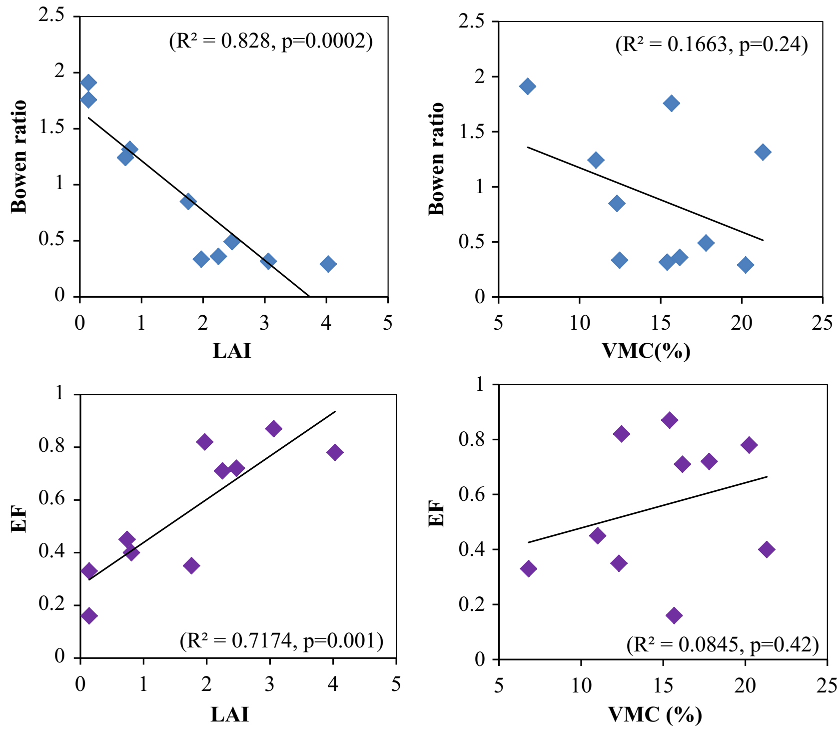

Figure 7. Relationship between Bowen ratio, EF and LAI, VMC.

Evaporative fraction defines latent heat flux more precisely which is a fraction of the surface available energy utilized for latent energy or evapotranspiration. EF varied from 0.16 to 0.87 through both the seasons (figure 6). It has opposite behaviour than Bowen ratio because it increases with high LAI value. It had a highly significant positive correlation with LAI value ($R^2 = 0.72$, $p = 0.001$), which defines that LAI has more prominent relationship with *EF* and *LE* (figure 7). In fallow period, *EF* had low value due to low *LE* value.

Bowen ratio exhibited a negative correlation while *EF* had a positive correlation with soil moisture content (figure 7) because high soil moisture condition is more favourable for plant growth. With a steady plant growth, *LE* will increase and *H* will decrease. The agricultural research farm was an irrigated field so that no specific water stress condition was discernible but the trend clearly showed that soil moisture also affect the Bowen ratio and *EF* value.

3.4 *Relationship of energy fluxes with LAI and soil moisture*

Apart from Bowen ratio and *EF*, it is worthy to analyse the role of biophysical and hydrological variables, viz., LAI and soil moisture in controlling the partitioning of net energy into surface heat fluxes over maize-wheat system. As illustrated in figure 8, the LAI over the path length of LAS markedly describe variation in *H* and *LE*. In Kharif as well as in Rabi season, *LE* step up and down with LAI increment and decrement. *H* was less than *LE* at most of the crop season with LAI growth. Thus, *H* was increased at the end of the season with crop maturity and harvesting. So, LAI had a significantly positive correlation with *LE* ($R^2 = 0.80$), while a significantly negative correlation with *H* ($R^2 = -0.79$). There was a sharp decline in *H* and *LE* due to meteorological parameters like: in case of sharp fall in *H* on 9 September, 2014 was due to wind speed and temperature and low *LE* on 28 January, 2015 was due to temperature, on 11 February, 2015 was due to temperature, wind speed, *RH* and on 26 February, 2015 was due to relative humidity. Thus, it is clearly discussed that atmospheric turbulent energy fluxes (*H* and *LE*) is primarily affected by meteorological parameters like wind speed, temperature, relative humidity and solar radiation. These factors ultimately affect the turbulence, enhance eddies/turbulence and energy content of the fetch area of agricultural terrain. Average soil moisture

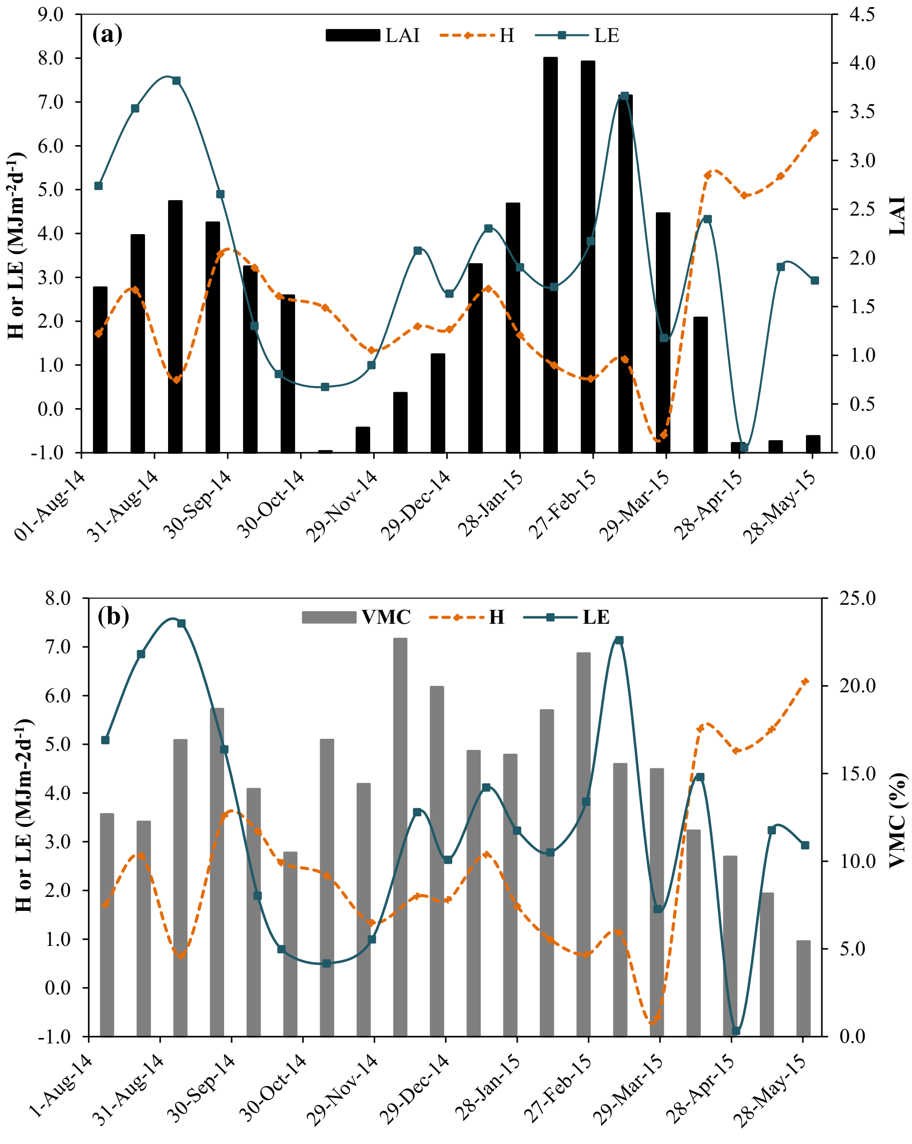

Figure 8. Seasonal H and LE variations with (**a**) LAI and (**b**) VMC (%).

with H and LE is depicted in figure 8(b). Average soil moisture was measured by weighing areal basis in the form of volumetric moisture content (%). The research farm was irrigated, so soil moisture was not a limiting factor in plant growth but surface energy partitioning gives an additional output as relation between turbulent energy and soil moisture. Soil moisture had a significantly negative correlation with H ($R^2 = -0.68$), while a positive correlation with LE ($R^2 = 0.03$).

3.5 *Daily evapotranspiration rate*

The seasonal profile of daily average evapotranspiration (ET) is presented in figure 9. ET refers the amount of latent energy which is used for transformation of water in vapours form. As the ET increases, it means proportion of latent energy enhances from total available energy. We found average ET rate was 1.58 mm d^{-1} for cropland and total amount of crop ET was 543 mm over the 12 months study period. The average evapotranspiration for Kharif and Rabi season was 2.04 and 1.45 mm d^{-1}, respectively. The higher rate of crop ET in Kharif season was because of more availability of solar radiation as compared to Rabi season and other meteorological parameters like relative humidity, wind velocity, etc.

4. Discussion

In general, the findings show that large aperture scintillometer is a reliable and robust instrument to measure fairly areal averaged heat fluxes. At the

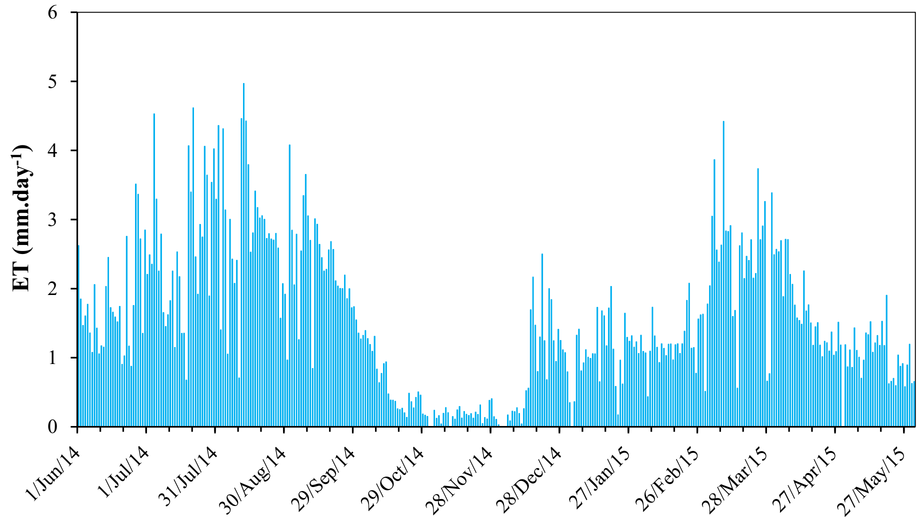

Figure 9. Seasonal profile of daily ET over the study period.

same, it requires little maintenance for continuous functioning. It performs nicely in all the seasons compared to eddy covariance system in terms of areal coverage and performance evaluation.

LAS measures intensity fluctuations of a collimated beam of incoherent light at spatial wavelengths within the inertial sub-range of eddy scales. McAneny *et al.* (1995) did an experiment over pasture with a transmitter–receiver separation of 350 m to estimate H and friction velocity (u_*). They defined the refractive index structure parameter more precisely with limitations in terms of inertial sub-range of scales and Fresnel zone. In same fetch, they installed an eddy correlation instrument (1-dimentional sonic anemometer and thermocouple) which provides measurements of fluctuations in vertical wind velocity and temperature. At unstable conditions, R_n, temperature and wind speed were investigated and compared with eddy correlation observation. They found, both are very encouraging with residual standard deviations of $0.04\,\text{ms}^{-1}$ and $25\,\text{Wm}^{-2}$ for u_* and H, respectively. No doubt there was some issues, i.e., saturation, poor temperature stability, thermal stability of the source but they are resolved with perfection of manufacturing and technology improvement.

It is well conceived that LAS has the potential to measure sensible heat and latent heat fluxes over a larger path length at our site. This performance of LAS is well supported if we look at the strong and significant relationship obtained between spatially representative ground measurements of ET governing factors and LAS measured fluxes. However, LAS measurements need to be analysed cautiously since poor visibility and stable stratification persisting sometimes cause substantial errors in average fluxes. At particular time in a day, few readings are erroneous or missed. Beyrich *et al.* (2002) also observed missing or erroneous observation particularly during heavy storm events in monsoon season at monsoon Lindenberg Observatory in the LITFASS area. This may happen in the monsoon time due to high precipitation. So, a keen observation in those situations is quite necessary at the time of energy balance study.

G/R_n ratio is an important parameter in surface energy balance study. Normally average G value was found to rarely exceed 10% of average monthly R_n, but it will be more than 10%–50% of net radiation in winter months. Cain *et al.* (2001) analysed the spatially averaged H over agriculture terrain of winter barley in Oxfordshire, UK and got a relationship between G and R_n. They confined that G varies from 10 to 40% of R_n in night hours. This occurs because of incoming net radiation is zero and only outgoing net radiation occurred at that time, therefore Rn was more exchanged in G at night hours. With this, there was a time lag between R_n and G peaks of about 1.5–2 hrs; this behaviour is because of thermal inertia of soil that means a slow heating process with respect to solar heating through solar radiation (Campbell and Norman 1998).

Seasonal pattern of energy fluxes (R_n, H, LE) is discernable; the realistic dynamics of H and LE with reference to R_n where H and LE vary more closely with net radiation. Guyot *et al.*

(2009) defined the same kind of energy pattern with a fairly well correlation between R_n and $H(R^2=0.61)$. Schuttemeyer (2005) and Guyot *et al.* (2009) quantified the fluctuation in H and LE with occurrence of rainfall, while an overall variation in energy pattern with the change in seasons and crops was concluded in this study.

Bowen ratio has a significant negative correlation with LAI ($R^2 = 0.83$). As crop grows, LAI will increase which enhances the LE in totality and decreases B value. In this study, minimum B value was estimated in August (0.33) and February (0.29) which shows that B value was maximum at season starting and ending while minimum at mid of the season at the non-moisture deficit condition. Meijninger and De Bruin's (2000) study on cotton field showed the variation of B value as 0.3 and 1 with irrigated and non-irrigated field condition, respectively. With this data measurements, H value was also countered less in the irrigated field condition which clarify that at the availability of moisture condition, H will decline and LE will enhance normally.

EF varies with crop growth and phenology which ultimately define that more LE is due to higher plant growth. Thus, EF was higher in the period of more vegetative growth. Guyot *et al.* (2009) explained EF on the basis of rainfall occurrence and observed similar pattern of EF at the rainfall events (similar to a condition of high LE).

5. Conclusions

The purpose of this study was to understand diurnal and seasonal variation in energy balance components (R_n, G, H and LE) of an agricultural landscape with latest scintillometry technique. In order to facilitate development of satellite based application for ET and drought monitoring, the LAS was set up at the agricultural research farm of Indian Agricultural Research Institute, New Delhi for a complete cropping pattern of mainly dominated by maize in Kharif and wheat in Rabi with fallow period in 2014–2015. Large aperture scintillometer (LAS) is a sophisticated instrument which is used for energy balance, energy partitioning, aerodynamic roughness, turbulence study over a path length of 990 m which was installed at research farm. LAS measurement, AWS data with biophysical parameters (crop LAI, soil moisture) were used for the study of surface energy fluxes and made relationship with crop growth profile and allocation of energy in the form of sensible, latent and ground heat fluxes. A complete energy balance was done with a comparative relationship with biophysical parameters (LAI and soil moisture). Weighted average was done for *in-situ* field measurements to get a relationship with turbulent heat fluxes. B and EF values are also quantified with different months and variation with crop phenology was examined.

R_n, H, G and LE varied from 1.52 to 10.15, 0.88 to 5.47, –0.66 to 1.29 and 0.40 to 6.83 $\mathrm{MJm^{-2}d^{-1}}$, respectively throughout the study period. Net radiation altered monthly as Earth–Sun distance changes. H and LE follows the R_n trend and they varied according to crop growth and vigour which can inter-change with cropping conditions. The B value for both Kharif and Rabi seasons was 0.76 and 0.88 by scintillometer because of more cumulative LE in Kharif as compared to Rabi. During the crop season, LAI will enhance up to a certain extent and after that it decline with maturity and harvesting stage. With this, LE partitioning become higher as compared to H in crop period while H become higher in fallow period or beginning and end of the crop season. Thus, a positive correlation was found between LAI and LE ($R^2 = 0.80$) and a negative correlation was found with H and LAI ($R^2 = -0.79$). Soil moisture also had a significant negative correlation with $H(R^2 = -0.68)$. Total crop ET was 543 mm with an average of 1.58 $\mathrm{mmd^{-1}}$. In the case of daily ET estimation, Kharif season had more ET as compared to Rabi due to higher intensity of solar radiation and time period. This study defines the pattern of energy fluxes with crop season and fallow period. A clear trend was established that B value is more at the start and end of crop season whereas less in mid of the life span of crop. Because of this, with crop growth, LE will increase and B value will decrease. EF has just opposite trend than B value.

Experiments with LAS over large and relatively homogeneous agroecosystem are critical for accurate and large-area representative measurement of ET and also useful in calibration and validation programme of geostationary satellite (viz., Kalpana VHRR, INSAT-3D and MSG-SEVIRI). Additionally, it can be used in developing of crop simulation model, new remote sensing energy balance algorithm and their calibration and validation. It has a major advantage to evaluate RS-EB flux which represents large spatial coverage that is more reliable with the RS pixel sizes than other flux estimation methods like Lysimetry or Eddy covariance. Over mixed or heterogeneous terrain, the surface ET_c may be more spatially variable; in such condition, LAS and RS derived ET_c fluxes are comparable.

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