Journal of Agrometeorology

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 26 (1) : 18 - 24 (March - 2024)
https://doi.org/10.54386/jam.v26i1.2447
https://journal.agrimetassociation.org/index.php/jam

Research Paper

Surface energy fluxes and energy balance closure using large aperture scintillometer-based ET station on heterogeneous agricultural landscape in North India

ABHISHEK DANODIA[1*], N. R. PATEL[1], V. K. SEHGAL[2] and R.P. SINGH[3]

[1]*Agriculture and Soils Department, Indian Institute of Remote Sensing, Dehradun, Uttarakhand, India*
[2]*ICAR- India Agricultural Research Institute, Pusa Campus, New Delhi, India*
[3]*Indian Institute of Remote Sensing, Dehradun, Uttarakhand, India*
**Corresponding author: e-mail: abhidanodia@iirs.gov.in*

ABSTRACT

This study was carried out to understand the pattern of surface energy fluxes over a periodical scale and energy balance closure using Large Aperture Scintillometer and Micrometeorological tower. The standalone technique as 'Scintillometry' which observes the structure parameter of refractive index based on Monin-Obukhov Similarity theory, has the potential to measure the sensible heat flux precisely. This paper discusses the surface energy balance components and energy balance closure over a period of August 2017 to June 2018. The maximum mean energy fluxes Rn, G, H and LE were observed in September (98.6 Wm^{-2}), May (13.9 Wm^{-2}), June (53.3 Wm^{-2}) and August (82.1 Wm^{-2}), respectively. The overall mean ET was observed at the rate of 1.36 mm day^{-1} during the study period. This scintillometry technique may further use in evapotranspiration modelling from polar orbiting satellite to geostationary satellite over a heterogeneous and undulated landscape.

***Keywords**:* Scintillometry, energy flux, sensible heat flux, energy balance closure, evapotranspiration.

Accurate measurement and estimation of surface energy fluxes are the essential keystone for understanding earth's climate system and further mass, heat and momentum fluxes between surface and atmospheric boundary layer. Precise estimation of evapotranspiration (ET), water use and water availability at local to regional scale are quite crucial for quantitative assessment of water resources. Surface energy fluxes and its derived results may further be utilized in assessment of regional water balance, irrigation water requirement, water use efficiency, water budget, etc. (Chehbouni *et al.,* 2000; Ezzahar *et al.,* 2007; Danodia *et al.,* 2017, 2018; Mauder *et al.,* 2020; Elfarkh *et al.,* 2022) Large Aperture Scintillometer (LAS) observes energy fluxes over the large scale (few meters to kilometers scale) with fine temporal resolution for all possible landscape even in the homogenous and heterogeneous terrain (Meijninger *et al.,* 2002; Liu *et al.,* 2013; Bruin and Wang 2017; Danodia *et al.,* 2017). LAS has proved its reliability over other instrumentations i.e. Bowen Ration Energy Balance (BREB) and Eddy Covariance (EC) which are not much reliable for arid or semi-arid regions along the rigorous data quality check, gap filling, energy balance closure and small eddies (Leuning and King 1992; Haslwanter *et al*., 2009).

LAS works on the principle of Monin-Obukhov similarity theory and observe the structure parameter of refractive index to compute sensible heat flux over the defined path length. Chehbouni *et al.,* (2000) did the experimental study to investigate the potential and limitations of LAS over the complex terrain. While comparison with EC system, the overall performance of scintillometer is acceptable, even at heterogeneous and undulated topography. Zhang *et al.,* (2021) estimated sensible and latent heat fluxes at hilly area at kilometer scale using optical-microwave scintillometer and compared the results with EC estimates. As per the finding, the optical-microwave scintillometer is reliable approach which showed 2% higher H and 10% higher LE as compare to EC observed turbulent heat fluxes i.e. sensible heat flux and latent heat flux. Hitherto, the LAS based studies has illustrated its significance and acceptable performance statistics within heterogeneous and complex terrain.

***Article info - DOI**:* *https://doi.org/10.54386/jam.v26i1.2447*
Received:20 November 2023; Accepted: 5 February 2024; Published online : 1 March 2024

The surface energy balance (SEB) closure depicts the energy status as unclosed or closed energy balance in the particular ecosystem. The closed system represents the accurate and near to ideal condition of SEB while unclosed system elucidates the biasness or ambiguity in the SEB, measured by instrumentation or model. In general, residual energy balance equation is extensively used for assessment of net available energy and turbulent heat flux, which inherent the minor energy fraction with LE or net available energy. Thus, the SEB closure analysis may clearly exemplify the preciseness of the observed energy components.

The main objectives of this paper are (a.) to define the temporal variability i.e. diurnal and seasonal energy fluxes and ET at daily to monthly scale, (b.) LAS derived SEB closure at monthly scale, (c.) to assess the correlation and relative weights of weather variables with respect to ET rate.

MATERIALS AND METHODS

Site description

The experimental agricultural research farm of ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi was the research cum experimental site with geographical location as 28.63°N, 77.15°E and an elevation of 220 m above sea level (Fig. 1). The location has sub-tropical to semi-arid climate where majority precipitation amount is received in monsoon season only. The maximum and minimum temperature observed in June and January, respectively while maximum and minimum relative humidity (RH) observed in August-September and May, respectively (Danodia *et al.,* 2017).

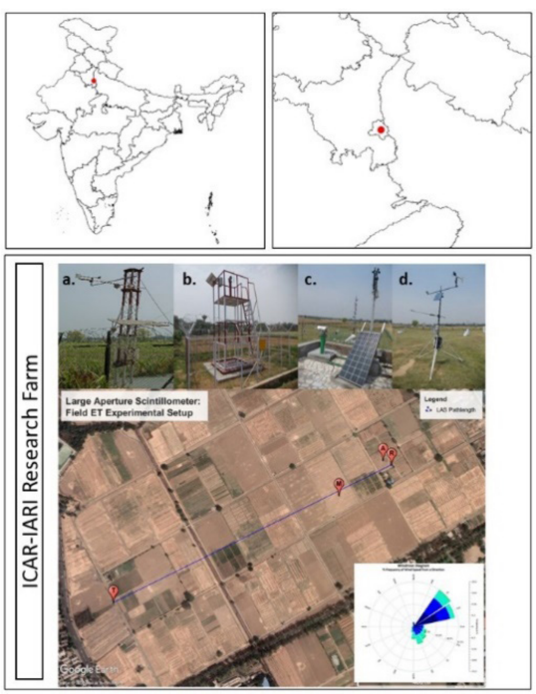

Fig. 1: ET station set-up at ICAR-IARI research farm; a. Micrometeorological tower, b. LAS transmitter, c. LAS receiver, d. Automatic weather station

Large aperture scintillometer (LAS)

The upgraded instrumentation of LAS was developed by Wageningen University, The Netherlands with improved electronics. A large aperture scintillometer (LAS, Kipp & Zonen Inc.) comprises transmitter, receiver, automatic weather station and data logger in-built with LAS receiver. The LAS observes structure parameter of refractive index (which is mainly caused by temperature and humidity fluctuation (Bruin and Wang 2017; Danodia *et al.,* 2018).

$$C_n^2 = \frac{\overline{[n(x)-n(x+r)]^2}}{r^{2/3}} \qquad \text{Eq. 1}$$

where, n(x) and n(x+r) depict the refractive index at location x and (x+r), respectively. Thus, the distance between them is r.

Ultimately, the sensible heat flux is calculated with the assumption of local free convection condition along the structure parameter of temperature and humidity are perfectly correlated (Meijninger *et al.,* 2002; Bruin and Wang, 2017).

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

Where, C_p is the specific heat of air at constant pressure, b = 0.57 is an empirical constant, d is the displacement height, g is the gravitational constant and C_T^2 is the structure parameter of temperature.

Details of instrumentation & observations

The details are illustrated in Table 1 which comprises all description of instruments/ sensors augmented at agricultural research farm of ICAR-IARI, New Delhi. All the sensors are high response sensors, observe the parameters at 10Hz frequency and finally compile the data into 5 min interval. The observations from 23 Aug 2017 to 30 Jun 2018 were used for this study while in between 21 Dec 2017 to 7 Feb 2018 data were missing due to technical limitations of functioning of instrumentation. Along this, MODIS satellite observed normalized difference vegetation index (NDVI) and enhance vegetation index (EVI) on daily scale were also used in correlation analysis for the same period. It defines the contribution of crop growth in terms of spectral indices.

Energy balance closure

The surface energy balance (SEB) is one of the decisive components in quantification of surface energy fluxes and its distribution in understanding the energy exchange process in the local ecosystem i.e. agricultural, forest, water etc. The surface energy balance can estimated using surface energy balance equation as (Allen et al., 1998; Mauder et al., 2020);

$$R_n = H + LE + G + \Delta E + M \qquad \text{Eq. 3}$$

Where Rn is net radiation, H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux, ΔE is the heat stored or released in the plant and M is the used energy in metabolic activities. Although the major contribution of energy fluxes is from H and LE in net available energy. While the ΔE and M includes the heat exchange as storage or release via the condition of advection, vertical divergence, non-stationary and surface heterogeneities (Mauder *et al.,* 2020). Here, the LE was computed using residual

Table 1: The sensors used, their make and parameters measured by them for the study

Instruments	Meteorological drivers	Sensors (Make/ Model)	Height/ Depth (m)	Used in/for
Large Aperture Scintillometer	Sensible heat flux (H)	Large aperture scintillometer (Kipp & Zonen: MK- II)	3.7	SEB & Crop ET
Automatic Weather Station	Net radiation (Rn)	Net radiometer: Kipp & Zonen: NR-LITE	2.0	SEB, Crop ET & Reference ET
	Incoming radiation (Rin)	Pyranometer: Kipp & Zonen: CMP3	3.0	
	Air temperature (T)	Campbell Scientific: CS 215	1.5	
	Relative humidity (RH)	Campbell Scientific: CS 215	1.5	
	Wind speed (WS)	03002-L RM Young Wind monitor	3.0	
	Wind direction (WD)	03002-L RM Young Wind monitor	3.0	
	Soil heat flux (G)	HukseFlux SC	0.1	
Micrometeorological Tower	Radiation (Four components)	CNR4 Kipp & Zonan: Net Radiometer	3.0	SEB, Crop ET & Reference ET
	Soil heat flux (G)	HukseFlux SC	0.25	
	Air temperature (T)	Rotronics Hygroclip 2	2.0 and 3.0	
	Wind speed (WS)	03002-L RM Young Wind monitor	3.0	
	Relative humidity (RH)	Rotronics Hygroclip 2	2.0 and 3.0	
	Wind direction (WD)	03002-L RM Young Wind monitor	3.0	

energy balance equation and further ET was calculated at 5 min interval using EVATION software of large aperture scintillometry technique.

Energy balance closure (EBC) may exist with assumption of perpendicular flux movement and two-dimensional surface exchange in horizontally uniform condition. EBC may be estimated by statistical regression of turbulent heat flux (H+LE) and net available energy flux (Rn-G) with the hourly averaged fluxes. EBC was computed using ordinary least squares method as linear regression model (Liu *et al.,* 2013; Mauder *et al.,* 2020). The EBC defines the measured parameters accuracy in terms of overestimation or underestimation when regression line is plotted. The EBC problem may magnify due to few reasons such as (a) sensor/ instrument observational error, (b) mathematical error during data processing or computation, (c) additional sources of heat/ energy, (d) horizontal/ vertical flux divergence and (e) advection. This is still point of research to quantify the EBC problem and its reasons. In this paper, we elaborately discuss the EBC at monthly and annual scale which depict the significance characteristics of scintillometry for SEB at spatial scale.

Statistical analysis of energy fluxes and ET

As the daily observed energy fluxes and ET have the noteworthy variability at the daily as well as monthly scale. With the seasonal progression (Kharif, Rabi and fallow), the ET rate is also varying which has dependency on different weather variables. Therefore, the statistical analysis was done to evaluate the correlation of ET with weather variables along satellite derived spectral vegetation indices (referred to crop vigor/ growth). Besides this, relative weight analysis (RWA) was done using ET and weather variables (Rn, T, RH, WS) at the seasonal scale to define the contribution of weather variables upon ET rate. The statistical analysis was done using R programme.

RESULTS & DISCUSSIONS

Surface energy fluxes at diurnal & seasonal scale

Diurnal pattern of the surface energy fluxes depicts the variation in different components of energy fluxes. Fig. 2 illustrates the same over the period of August 2017 to June 2018. Here, LAS and AWS integrated 5 min interval observations were analyzed to derive the energy fluxes and derive all fluxes at hourly scale. Further, it was combined at daily to monthly scale using average function, which represent the overall diurnal pattern from 0:00 Hours to 24:00 Hours at monthly level. The monthly averaged Rn was found at the maximum and minimum at April (437 Wm^{-2}) and December (198 Wm^{-2}), respectively at noon hour. The decreasing trend in peak monsoon to post monsoon and winter while increasing trend in summer was observed in Rn and G. The H and LE have the distinct pattern under the cropping environment where if one energy flux is increasing than other one is decreasing. Therefore, during crop growing time, the LE is increasing with decreasing H while during the maturity and harvesting, the H was increasing with decreasing LE. The results were comparable with findings of Danodia *et al.,* (2017, 2018).

The box plot results were formulated using monthly average values of all surface energy fluxes. Fig. 3 depicts the capriciousness of the energy fluxes with upper and lower meniscus of the energy fluxes. The results reveal that the variation in the energy fluxes is quite higher in monsoon period compared to other seasons because of fluctuated net available energy, higher rate of crop growth as well as the cloudiness during the same season. As

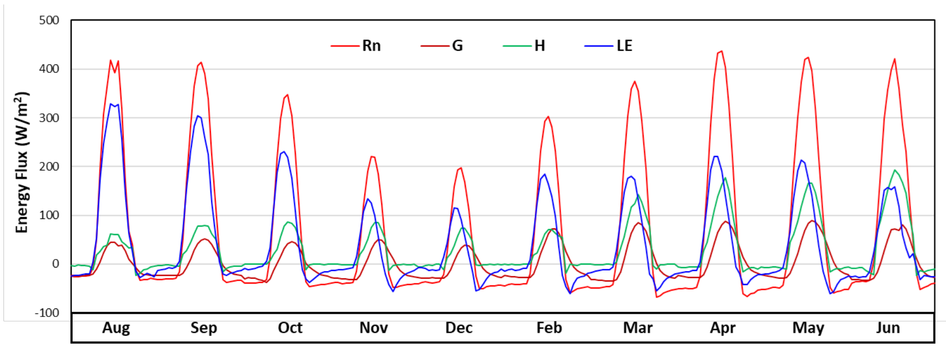

Fig. 2: Diurnal pattern of surface energy fluxes

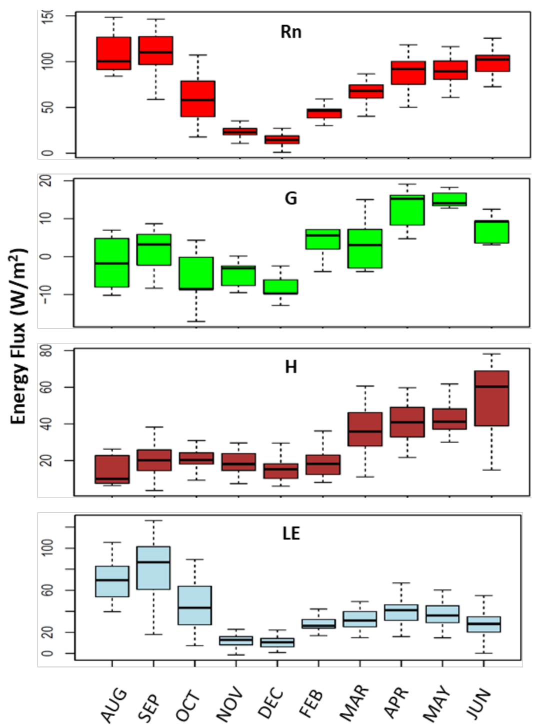

Fig. 3: Box plot representation of surface energy fluxes at monthly scale

per comparative analysis, the highest mean Rn, G, H and LE were received in September (98.6 Wm^{-2}), May (13.9 Wm^{-2}), June (53.3 Wm^{-2}) and August (82.1 Wm^{-2}), respectively.

Energy balance closure at monthly scale

LAS observed EBC found more closer or less closure problem for the study area (pathlength). The scatter plot was drafted using hourly turbulent heat flux and net available energy flux which shows that the all months have 0.99 coefficient of determination except November and June (R^2=0.98) and closer to 1:1 scatter plot line. It was found statistically significant ($p<0.01$) for all the months. Although LAS gives slightly overestimation in compuation of turbulent energy fluxes (H & LE). The mean bias error (MBE) was 2.47 Wm^{-2} for the study period where the positive value indicate the overestimation. The EBC at monthly scale is illustred in Fig. 4 while last sctter plot defines the overall annual EBC of all energy fluxes. Liu *et al.,* (2013) did the EBC study for three sites using EC observations, where they found a variability of 79% to 89% in the study. Zhang *et al.,* (2021) computed the EBC for EC as well as LAS. They got 0.86 to 0.87 R^2 for LAS and 0.77 R^2 for EC. They also defined about the overeatimation of LAS.

Comparative analysis of energy fluxes and ET

The daily averaged ET and EF were illustrated in Fig. 5 which is compiled using SEB derived results. The maximum and minimum daily average ET was observed in August (4.99 mm day^{-1}) and December (0.02 mm day^{-1}), respectively as similar to the maximum and minimum average ET on monthly basis. This is due to more vegetative growth and water availability in August while less net radiation with lower vegetative growth in December. The overall mean ET was observed at the rate of 1.36 mm day^{-1} during the study period. EF depicted the similar trend as ET on daily scale which can be used as proxy of ET.

The correlation matrix of Pearson correlation coefficient

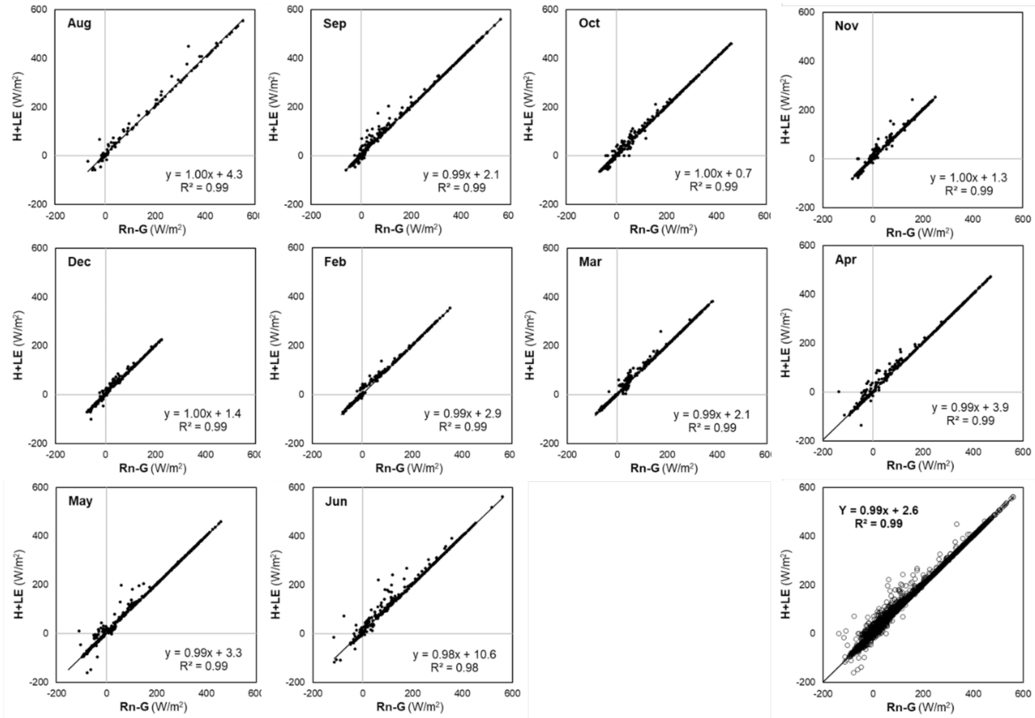

Fig. 4: Scatter plot of turbulent heat flux and net available energy flux for EBC

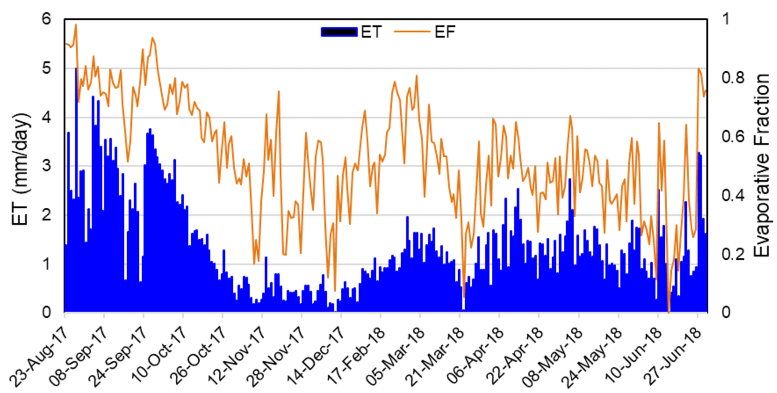

Fig. 5: ET and EF on daily scale during the study period

(r) for observed ET with SEB components, remote sensing derived spectral vegetation indices and meteorological parameters are illustrated in Fig. 6 derived using daily observed data of all parameters. Here, observed ET has the highest significant correlation (r = 0.86) with net radiation, followed by air temperature (r = 0.61) and relative humidity (r = 0.60), which define the usefulness of radiation components and other parameters. However, net radiation has the highest significant correlation (r = 0.68) with air temperature while sensible heat flux (H) has the significant correlation with relative humidity (r = -0.58), incoming radiation (r = 0.50) and wind speed (r = 0.50). ET has comparative higher correlation (r = 0.48) with enhanced vegetation index (EVI) as compare to NDVI (r = 0.32). The correlation coefficient (r) is represented with level of significance in correlation matrix (Fig. 6).

The monthly average net available energy (Rn & G) and LAS derived turbulent heat flux (H & LE) were shown in Table 2. The portioning of LE was higher during peak crop growing season as compare to fallow period. According to the sign convention, the positive values show downward direction to the surface while negative value show upward direction from surface for energy flux.

The principal weather parameters are solar radiation/ net radiation, air temperature, humidity and wind speed which significantly affect the ET (Allen *et al.,* 1998). Thus, the variable importance analysis was done using relative weights analysis (RWA) with ET. The results illusrated in Fig. 7 reveals that net radiation, air temperature and relative humidity have positive influence on ET while wind speed has negative influence on ET during overall period. The solar radiation is the key components which has the maximum contribution in accelaration of ET rate in agricultural landsacpe. Air tempearture and realtive humidity are closely associated with each other and have high weightage on rate of ET during crop growing season. The air temperature play distinct role during fallow period.

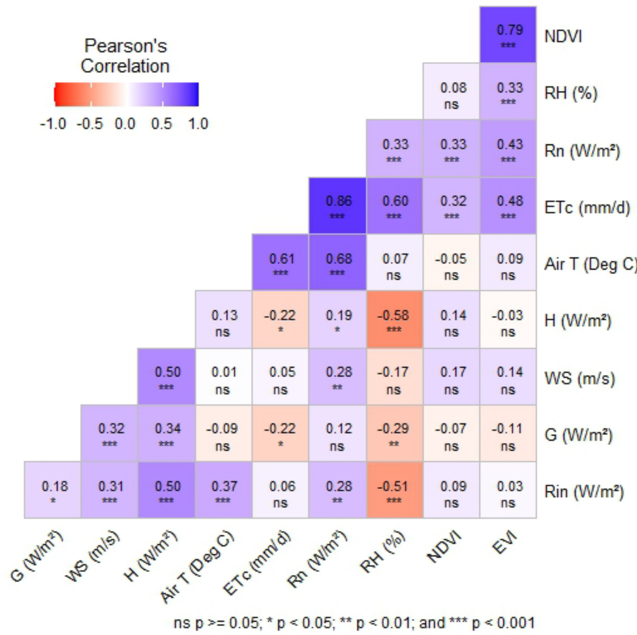

Fig. 6: Pearson correlation coefficient (r) of observed ET with different components of SEB and meteorological parameters

Table 2: Comparative analysis of energy fluxes with ET rate at monthly scale

Month	**Rn** (W/m²)	**G** (W/m²)	**H** (W/m²)	**LE** (W/m²)	**ET (mm day^{-1})**
August, 2017*	100.4	-0.8	14.5	82.1	6.44
September, 2017	98.6	0.9	22.2	77.1	5.80
October, 2017	60	-5.5	21.1	45.6	4.62
November, 2017	21.9	-5.1	18	11.3	2.63
December, 2017*	14.5	-8.3	14.2	8.3	2.30
February, 2018*	44.3	4.1	18	26.7	3.80
March, 2018	65.8	4.2	35.1	29.1	4.02
April, 2018	87.9	11.2	40.6	40.8	4.44
May, 2018	92	13.9	43.2	36.8	4.42
June, 2018	98	8	53.3	32.1	3.04

**Represents the missing observation in respective month.*

This may be because of no active crop growth in fields as well as mositure was not available for speedy ET rate.

CONCLUSIONS

This study was conducted to define the diurnal and seasonal pattern of surface energy fluxes over the LAS path length which comprise the heterogeneous landscape under irrigated condition. Besides this, the EBC is an important component, which illustrate the energy balance status of the system (LAS observed energy fluxes) during the analysis of surface energy balance equation. The results revealed that Rn may varies with season while LE and H varies with crop growth and phenological stages. LAS derived EBC has realistic energy closure with slight overestimation during few temporal scales. This study depicts the robustness of LAS set-up for surface energy fluxes and ET observations over a path length which may further be used in various study i.e. remote sensing-based energy balance, evapotranspiration modelling, model validation, irrigation planning and water budgeting etc.

ACKNOWLEDGEMENT

We would like to say thanks to Group Head, AFEG, IIRS for kind support. This research work was carried-out as a part of TDP project funded by ISRO. The authors are also very much thankful to the anonymous reviewers.

Data availability: Data are available on request basis only.

Conflict of Interests: The authors declare that there is no conflict of interest related to this

Authors contribution: **A. Danodia**: Data collection, Data Analysis, Conceptualization, Methodology, Visualization, Writing-original draft, Writing-review; **N.R. Patel**: Resources, Supervision, Writing-

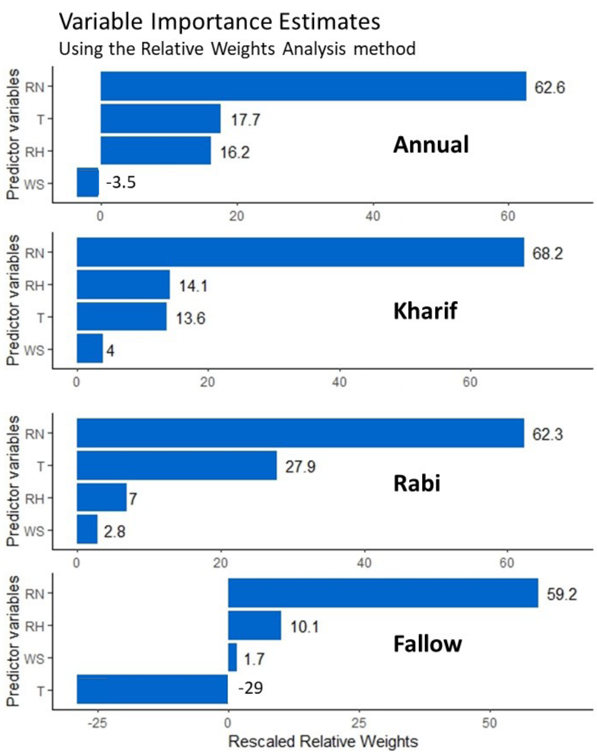

Fig. 7: Rescaled relative weights of principal weather parameters on ET rate

review and editing; **V.K. Sehgal**: Resources, Data collection; **R.P. Singh**: Resources, Supervision

Disclaimer: The contents, opinions, and views expressed in the research communication published in the Journal of Agrometeorology are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

Publisher's Note: The periodical remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements FAO irrigation and drainage paper No. 56. https://www.fao.org/3/X0490E/x0490e00.htm

Bruin H De, and Wang J. (2017). Scintillometry : A Review. https://www.researchgate.net/publication/316285424_Scintillometry_a_review.

Chehbouni, A., Watts, C., Lagouarde, J. P., Kerr, Y.H., Rodriguez, J. C, Bonnefond, J. M., Santiago, F., Dedieu, G., Goodrich, D. C. and Unkrich, C. (2000). Estimation of heat and momentum fluxes over complex terrain using a large aperture scintillometer. *Agric. Forest Meteorol.,* 105: 215–226.

Danodia, A., Sehgal, V. K., Patel, N. R., Dhakar, R., Mukherjee, J., Saha, S. K. and Kumar, A. S. (2017). Assessment of large aperture scintillometry for large-area surface energy fluxes over an irrigated cropland in North India. *J. Earth Syst. Sci*, 126: 69.

Danodia, A., Sehgal, V.K., Mukherjee, J., Das, D.K. and Patel, N.R. (2018). Diurnal and seasonal patterns of sensible and latent heat fluxes from irrigated agroecosystem by large aperture scintillometry. *J. Agrometeorol.,* 20 (special issue): 102–106.

Elfarkh, J., Simonneaux, V., Jarlan, L., Ezzahar, J., Boulet, G., Chakir, A. and Er-Raki, S. (2022). Evapotranspiration estimates in a traditional irrigated area in semi-arid mediterranean . Comparison of four remote sensing-based models. *Agric. Water Manag.,* 270: 107728. https://Doi.Org/10.1016/J.Agwat.2022.107728

Ezzahar, J., Chehbouni, A., Hoedjes J. C. B., Er-Raki, S., Chehbouni, A, Boulet G., Bonnefond, J. M. and De Bruin, H. A. R. (2007). The use of the scintillation technique for monitoring seasonal water consumption of olive orchards in a semi-arid region. *Agric Water Manag*., 89: 173–184. https://Doi.Org/10.1016/J.Agwat.2006.12.015

Haslwanter, A., Hammerle, A. and Wohlfahrt, G. (2009). Openpath Vs. Closed-Path Eddy Covariance Measurements Of The Net Ecosystem Carbon Dioxide And Water Vapour Exchange: A Long-Term Perspective. *Agric. Forest Meteorol.*, 149: 291–302.

Liu, S.M., Xu, Z.W., Zhu, Z.L., Jia, Z.Z. and Zhu, M.J. (2013). Measurements of evapotranspiration from eddy-covariance systems and large aperture scintillometers in the hai river basin, china. *J. Hydrol.,* 487, 24–38. https://Doi.Org/10.1016/J.Jhydrol.2013.02.025

Leuning, R. and King, K.M. (1992). Comparison of eddycovariance measurements of CO_2 fluxes by open- and closed-path CO_2 analyzers. *Bound.-Layer Meteorol.*, 59: 297–311.

Mauder, M., Foken, T. and Cuxart, J. (2020). Surface-Energy-Balance Closure Over Land: A Review. *Bound.-Layer Meteorol.*, 177: 395-426.

Meijninger, W. M. L., Hartogensis, O. K, Kohsiek, W., Hoedjes, J. C. B., Zuurbier, R. and De Bruin H.A.R. (2002). Determination Of Area-Averaged Water Vapour Fluxes With Large Aperture And Radio Wave Scintillometers Over A Heterogeneous Surface - Flevoland Field Experiment. *Bound.-Layer Meteorol.*, 105: 63–83. https://Doi.Org/10.1023/A:1019683616097

Zhang, G., Zhang, J. and Meng, P. (2021). Estimation Of Kilometer-Scale Heat Fluxes Over A Hilly Area In Northern China Using An Optical-Microwave Scintillometer. *Agric. Water Manag*., 244. https://Doi.Org/10.1016/J.Agwat.2020.106582