Tropical Ecology (2022) 63:387–397
https://doi.org/10.1007/s42965-021-00216-8

International Society for Tropical Ecology

RESEARCH ARTICLE

Measuring evapotranspiration by eddy covariance method and understanding its biophysical controls in moist deciduous forest of northwest Himalayan foothills of India

Ritika Srinet[1] · **Subrata Nandy**[1] · **Taibanganba Watham**[1] · **Hitendra Padalia**[1] · **N. R. Patel**[1] · **Prakash Chauhan**[1]

Received: 15 February 2021 / Revised: 16 November 2021 / Accepted: 10 December 2021 / Published online: 29 January 2022

Abstract
Forests play a pivotal role in carbon and water cycles by governing the exchanges of CO_2 and H_2O between the terrestrial biosphere and the atmosphere. The evapotranspiration (ET) is the variable, which links these cycles. The eddy covariance (EC) method provides direct, high-frequency observations of ET of an ecosystem. The present study was carried out in a moist deciduous plant functional type (PFT) of northwest Himalayan foothills of India to estimate ET using the EC flux tower measurements and to study its biophysical controls from 2016 to 2018. The variability of sensible (H) and latent (LE) heat fluxes was also studied. The mean diurnal variation in H was from -1.31 to 109.35 Wm^{-2} whereas LE ranged from 4.47 to 186.89 Wm^{-2}. The mean annual ET for 2016–2018 was found to be 693.67 ± 46.70 mm $year^{-1}$. The highest diurnal variability in ET was witnessed during the post monsoon season followed by the monsoon, winter, and dry summer seasons. A relative weight analysis with multiple regression model was implemented to understand the control of biophysical variables on ET at an 8-day time scale. A combination of incoming solar radiation (R_g), leaf area index (LAI), vapour pressure deficit (VPD), air temperature (T_{air}), soil water content (SWC), and precipitation was able to explain 73% of the variability of ET at 8-day time scale. The analysis revealed that in the moist deciduous PFT the ET was limited by the availability of energy. The present study is the first-ever attempt to report the direct estimates of ET for an Indian forest.

Keywords Biophysical control · Eddy covariance · Evapotranspiration · Moist deciduous plant functional type · Northwest Himalayan foothills

Introduction

The hydrological cycle is a vital component in the functioning of an ecosystem as it links various biogeochemical and energy cycles (Wilson and Baldocchi 2000). The forests are a significant part of the hydrological cycle (Roberts 2009). In tropical and sub-tropical areas, the forests receive most of the water through precipitation. A part of water, received in the form of precipitation, is intercepted by the canopy and evaporated from the surface of vegetation before reaching the soil. The rate of water infiltration, run-off, and percolation are also affected by the density and depth of the root channels (Dunne et al. 1991). During CO_2 assimilation by the process of photosynthesis, leaves take up CO_2 by diffusion through the stomatal pores; simultaneously they also lose water by the process of transpiration.

The transfer of water from the Earth's surface to the atmosphere, through the process of evaporation from various sources including plant surface, soil, and transpiration from plants is known as evapotranspiration (ET) (Hamon 1960). This water transfer or exchange comprises a change of state of water from liquid to vapor, which absorbs energy and cools the land surface (Wang and Dickinson 2012). The latent energy involved in ET is termed as the latent heat of vaporization. At the ecosystem level, the partitioning of energy, available through the net radiation, into ET (latent heat flux, LE) and sensible heat flux (H) affects various aspects of weather and climate (Wever et al. 2002).

Evapotranspiration (ET) provides a nexus between the terrestrial water, carbon, and energy exchange processes (Monteith 1965; Sheffield et al. 2010; Wang and Dickinson

---

✉ Subrata Nandy
subrato.nandy@gmail.com

[1] Indian Institute of Remote Sensing, Indian Space Research Organisation, Department of Space, Govt. of India, Dehradun 248001, India

2012). It has been considered a predominant variable needed to understand the efficiency of water utilization by vegetation (Allen et al. 1998; Anderson et al. 2011; Nandy et al., 2021). It is also an indicator of extreme events like flash droughts (Anderson et al. 2013; Otkin et al. 2016). Moreover, long-term changes in ET at a regional scale can ascertain the persistent drought and desertification caused by climate change (Sheffield et al. 2012; Greve et al. 2014; Mao et al. 2015). Hence, robust and long-term ET measurements are vital to enhance the understanding of the global water cycle and hydrological function of forests (Tong et al. 2017).

To estimate ET, several methods have been established including simple empirical methods, soil–water budget methods, Bowen ratio, or eddy covariance (EC)-based measurements and modelling techniques, which have been implemented at varying scales. The analytical methods involve discrete measurements of transpiration, rainfall interception, and soil and understory ET using various tools like sap flow sensors (Ford et al. 2007), rain gauges above and below canopy (Herbst et al. 2008), and measurement chambers (Ford et al. 2007) whereas the soil water budget method depends on the resolution of the soil water budget equation using rainfall, soil water content (SWC) and drainage measurements (Schwärzelet al. 2009). In forests, the species composition, distribution, and sapwood area of different species affect the upscaling of sap flow-based studies from tree to stand level (Watham et al. 2017a). The variability in rainfall interception depends on the forest density, structure of the trees as well as on weather conditions (Soubie et al. 2016). The soil and understory ET in mature forests are usually low, but it depends on energy reaching the soil, thus, on leaf area index (LAI), hence, it can vary significantly for some ecosystems (Vincke et al. 2005). The information obtained from these methods is limited in their scope to explain the biophysical controls of ET on hourly to daily time scales (Baldocchi and Ryu 2011).

Lately, the ET and energy fluxes are being studied in several ecosystems using the EC technique. The EC-based method provides in situ, stand scale measurements of forest ET and energy partitioning with negligible interference (Baldocchi and Ryu 2011). These systems usually consist of instruments that allow high-frequency measurements of CO_2 and H_2O fluxes. These systems provide long-term valuable observations of fluxes (Wang and Dickinson 2012). There has been a steady increase in the application of the EC method because of its ability to directly measure the gas and energy exchange between ecosystems and the atmosphere over the forest areas (Baldocchi and Ryu 2011; Aubinet et al. 2012). Several EC flux towers have also been established over different forest ecosystems across India. The diurnal and seasonal variability of CO_2 fluxes has been reported for these forest ecosystems (Jha et al. 2013; Rodda et al. 2016; Deb Burman et al. 2017; Watham et al. 2017b, 2020). However, the dynamics of ET have not been studied in detail.

In general, for the process of photosynthesis to occur, the rate of CO_2 transfer from the atmosphere to the carboxylation sites is directly linked to the water loss occurring through the process of leaf transpiration (Marques et al. 2020). These exchanges occurring in an ecosystem are controlled by the interaction of various environmental factors, including incoming solar radiation (R_g), air temperature (T_{air}), vapor pressure deficit (VPD), and SWC, in combination with the vegetation biological processes like leaf emergence and development (Zha et al. 2013). It has been reported that these biophysical variables play a significant part in regulating the diurnal to inter-annual variability of ET (Baldocchi et al. 2004; Baldocchi and Xu 2007). Hence, an in-depth understanding of these controls is essential to assess how the changes in climate may affect the variability in ET. The present study aims to report the EC-based measurements of ET and energy fluxes, in the moist deciduous plant functional type (PFT) of northwest Himalayan (NWH) foothills of India for a period from 2016 to 2018. The main objective of the study is to document how ET and energy fluxes vary in the moist deciduous PFT. Additionally, it explores how the biophysical factors control ET in this ecosystem as it represents one of the major PFTs in the NWH foothills of India.

Material and methods

Study site

The study was conducted at Barkot Flux Site (BFS, 30° 06′ 44.40″ N, 78° 12′ 43.06″ E), which is located in the NWH foothills of Uttarakhand, India (Fig. 1). The elevation at the study site is 415 m above sea level which is relatively flat to undulating terrain. It has a monsoon-influenced humid subtropical climate. The site lies in the moist deciduous PFT (Srinet et al. 2020), which was also categorized as Tropical Moist Deciduous forest by Champion and Seth (1968). The overstory is dominated by sal (*Shorea robusta*) and its associates present in the area include *Terminalia tomentosa*, *Lagerstroemia parviflora*, *T. bellirica,* and *Syzygium cumini* (Nandy et al. 2017). The understory mainly comprises *Mallotus philippensis*, *Ehretia laevis,* and *Cassia fistula*. The maximum canopy height observed at the study site is approximately 32 m. It is a climax forest with a maximum LAI of 4.2 (Watham et al. 2020). The forest around the flux tower site experiences leaf fall from the end of February to the beginning of May (Srinet et al. 2019). The mean annual temperature observed from 2016 to 2018 was 21.87 °C and the annual precipitation was 1115.40 mm.

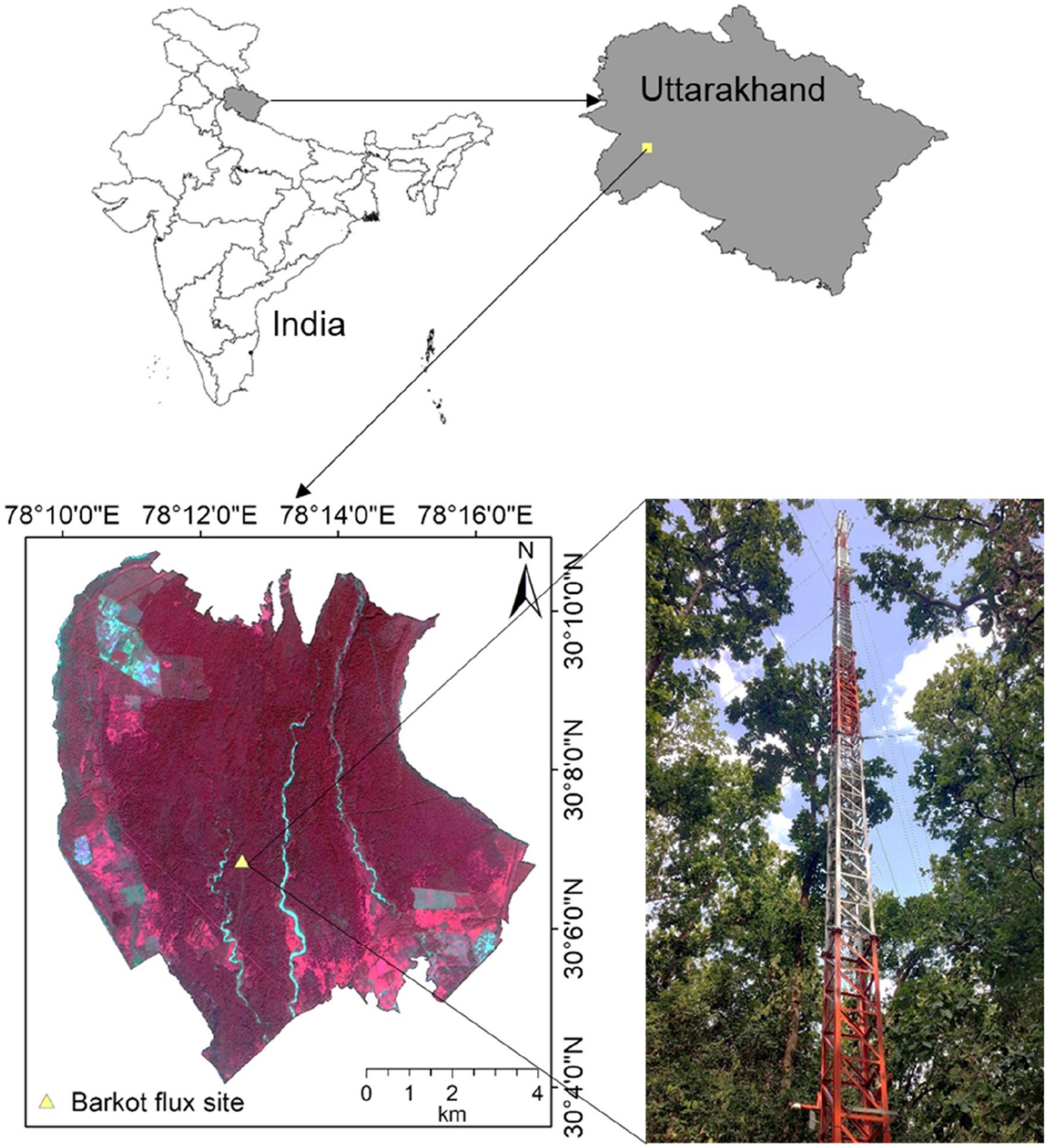


Fig. 1 Location of Barkot flux site

Data used

The study was conducted over 3 years, from 2016 to 2018. The energy and water fluxes between the forest and the atmosphere were measured using the EC method. The EC system installed at the site consists of an integrated CO_2/H_2O open-path infrared gas analyzer and 3D sonic anemometer (IRGASON, Campbell Scientific). It takes continuous 10 Hz measurements of CO_2 and H_2O fluctuations at 46 m height above the ground surface. R_g was measured at 46 m height using a 4-component net radiation sensor (CNR4-L, Kipp and Zonen, The Netherlands). T_{air} and relative humidity (RH) were measured at 6 levels (2 m, 4 m, 8 m, 16 m, 32 m, 48 m) using relative humidity and temperature probes (HygroclipsS3, Rotoronic, Switzerland). Soil temperature and SWC were measured at 5 levels (5 cm, 10 cm, 20 cm, 60 cm, 100 cm below the ground surface) using soil moisture and temperature sensor (CS650, Campbell Scientific). All these data were recorded using CR3000 data logger (Campbell Scientific, Logan, UT, USA). The meteorological data were recorded at half-hourly intervals.

To analyze the control of biophysical variables on ET, the observed biophysical variables including R_g, T_{air}, VPD, precipitation, and SWC were taken into account, whereas, the

LAI values were taken from the Moderate Resolution Imaging Spectroradiometer (MODIS) combined Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) 8-day composite dataset (MOD15A2H).

Data processing and analysis

The flux data collected by the EC system was processed using EddyPro 6.2.0 software (Li-COR Biosciences, USA) and carbon, water, and energy fluxes were calculated. The processing was carried out using the standard procedure which includes splitting the data into 30 min files; despiking; block averaging; 2D coordinate rotation; spectra correction; Webb, Pearman, and Leuning (WPL) and other corrections; and quality control (Burba 2013). For the night-time filter, frictional velocity (u*) filtering was applied to the obtained half-hourly time-series for 2016–2018. The 30-min mean fluxes were screened for precipitation periods, instrument failure, and out-of-range records. The data was checked for gaps and gap filling was carried out using the ReddyProc package (Wutzler et al. 2018) in R, using marginal distribution sampling (MDS) (Reichstein et al. 2005; Foltýnová et al. 2020).

Half-hourly ET over the study site was calculated as (Ma et al. 2017):

$$ET = \frac{LE}{L\rho_w} \tag{1}$$

where LE is the latent heat flux; L is the latent heat of vaporization of water (2.45 kJ g^{-1}); ρ_w is the density of water. To study the seasonal pattern of ET, based on the climatic variations and plant phenology, the year was divided into four seasons (Watham et al. 2020): (a) winter (DOY: 01 to 90), (b) dry summer (DOY: 91 to 181), (c) monsoon (DOY: 182 to 273), and (d) post-monsoon (DOY: 274 to 365) seasons.

A relative weight analysis (RWA) using a multiple regression model was carried out to understand the effect of variability of various biophysical variables including R_g, T_{air}, VPD, precipitation, SWC, and LAI on ET in R environment. As the biophysical variables were highly correlated, therefore, to understand their proportionate contribution to the regression model (R^2), considering both its unique contribution and its contribution when combined with other variables (Johnson 2000), the RWA was implemented. The LAI data was available at a temporal resolution of 8-days, hence, the RWA was carried out at 8-days timescale.

Results

Variations in energy fluxes and evapotranspiration

Variability of energy fluxes

Figure 2 shows the diurnal variation in the half-hourly means of H and LE for all the seasons from 2016 to 2018. The diurnal variation in H was the largest during the dry summer season (-6.72 to 207.83 W m^{-2} with the peak at 1300 h). The values of H ranged from -8.31 to 118.34 W m^{-2} in winter with a peak observed at 1230 h,

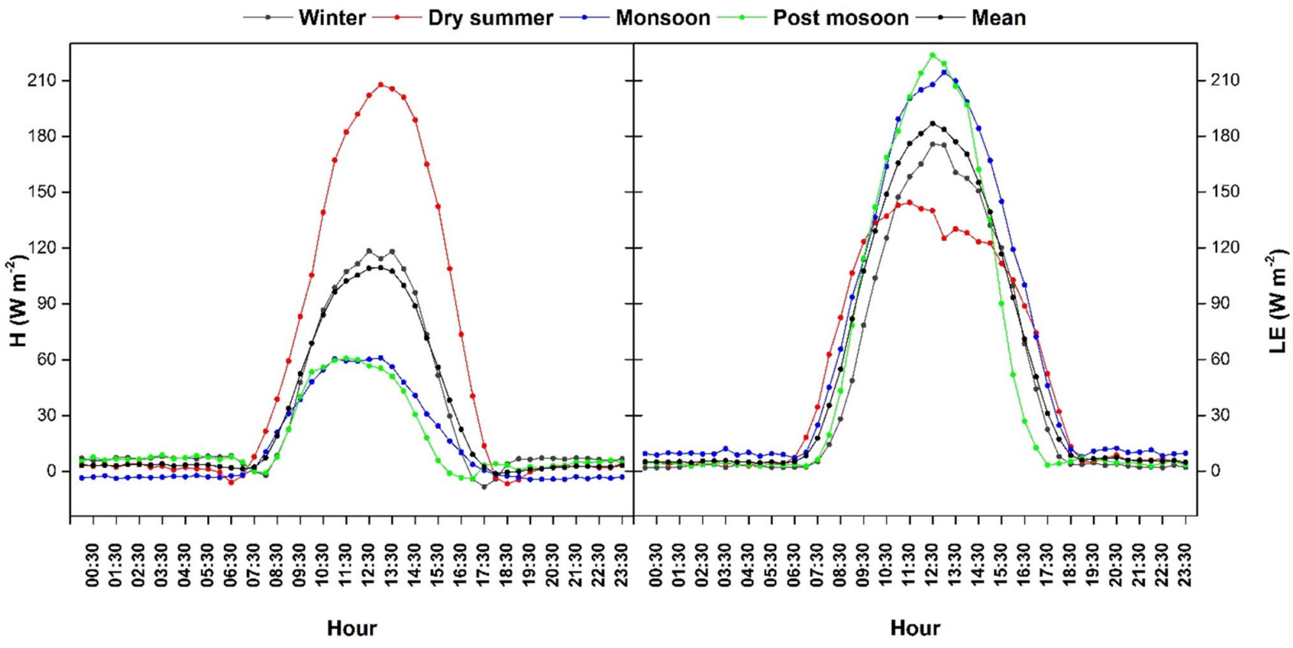


Fig. 2 Seasonal averaged diurnal variations of sensible (H) and latent heat flux (LE)

-4.34 to 61.03 W m^{-2} in monsoon with a peak at 1300 h, and -3.97 to 60.73 W m^{-2} in post-monsoon season with a peak at 1130 h. The mean diurnal variation in H for 2016 to 2018 was found to be from -1.31 to 109.35 W m^{-2}. The night-time values of H were found to be negative in all the seasons. The variability in LE was the highest in the post-monsoon season; it ranged from 2.52 to 223.54 W m^{-2} with a peak at 1230 h. LE ranged from 7.10 to 214.41 W m^{-2} in monsoon with a peak at 1300 h, 1.79 to 175.64 W m^{-2} in winter with a peak at 1230 h, and 2.72 to 144.31 W m^{-2} in dry summer with a peak at 1130 h. The mean diurnal variation in LE for the seasons ranged from 4.47 to 186.89 W m^{-2}.

Figure 3 represents the variability of mean daily H and LE from 2016 to 2018. H and LE values showed significant seasonal and day-to-day variation. The highest value of H was observed during dry summer whereas the highest value of LE was observed during the monsoon season. With the onset of the leaf-fall period, during the end of February to March, daily LE showed a decreasing trend and H showed an increase in values. H was found to be higher than LE in dry summer. H sharply decreased by the end of dry summer whereas LE started increasing. LE continued to increase and H tended to decrease at the beginning of the monsoon season. The value of H maintained a stable trend during monsoon and post monsoon seasons, whereas, LE decreased in post-monsoon season. However, the value of LE was always higher than H in monsoon and post-monsoon seasons.

Variability of evapotranspiration

The annual ET was found to be 693.67 ± 46.70 mm. The diurnal variation of ET is shown in Fig. 4. The highest diurnal variation was observed during the post-monsoon season (0.003 to 0.32 mm h^{-1}) followed by monsoon (0.01 to 0.31 mm h^{-1}), winter (0.002 to 0.25 mm h^{-1}), and dry summer (0.003 to 0.21 mm h^{-1}). The annual variation of ET at the study site is shown in Fig. 5. ET exhibited a multi-peak trend in all the 3 years. The daily ET varied from 0.19 to 4.27 mm day^{-1} in 2016, 0.25 to 4.07 mm day^{-1} in 2017, and 0.35 to 4.04 mm day^{-1} in 2018. The total ET was found to be 745.80 mm $year^{-1}$ in 2016, 679.52 mm $year^{-1}$ in 2017, and 655.67 mm $year^{-1}$ in 2018. The peak ET was observed during September, which was during the late monsoon period. Mean daily ET started increasing from January till March–April and reduced during the dry summer months with few fluctuations. The peak ET was observed in the monsoon season with a few dips in the values and it started reducing slightly again in post-monsoon season.

Biophysical control on evapotranspiration

To understand the influence of the local environment on ET, a statistical analysis was carried out. Seasonal variations in R_g, T_{air}, VPD, precipitation, and SWC vis-à-vis ET are presented in Fig. 6. The maximum R_g was observed during the end of the dry summer season while the minimum R_g was observed during the monsoon season. The R_g values showed significant day-to-day fluctuations apart from the

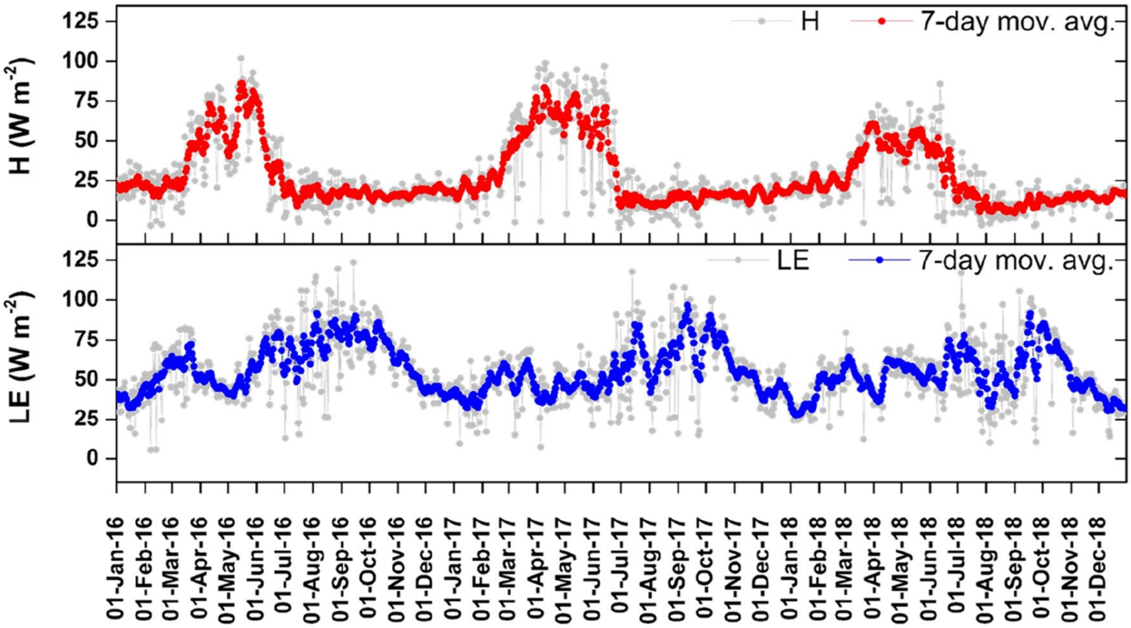


Fig. 3 Daily sensible (H) and latent (LE) energy variations at Barkot flux site from 2016–2018

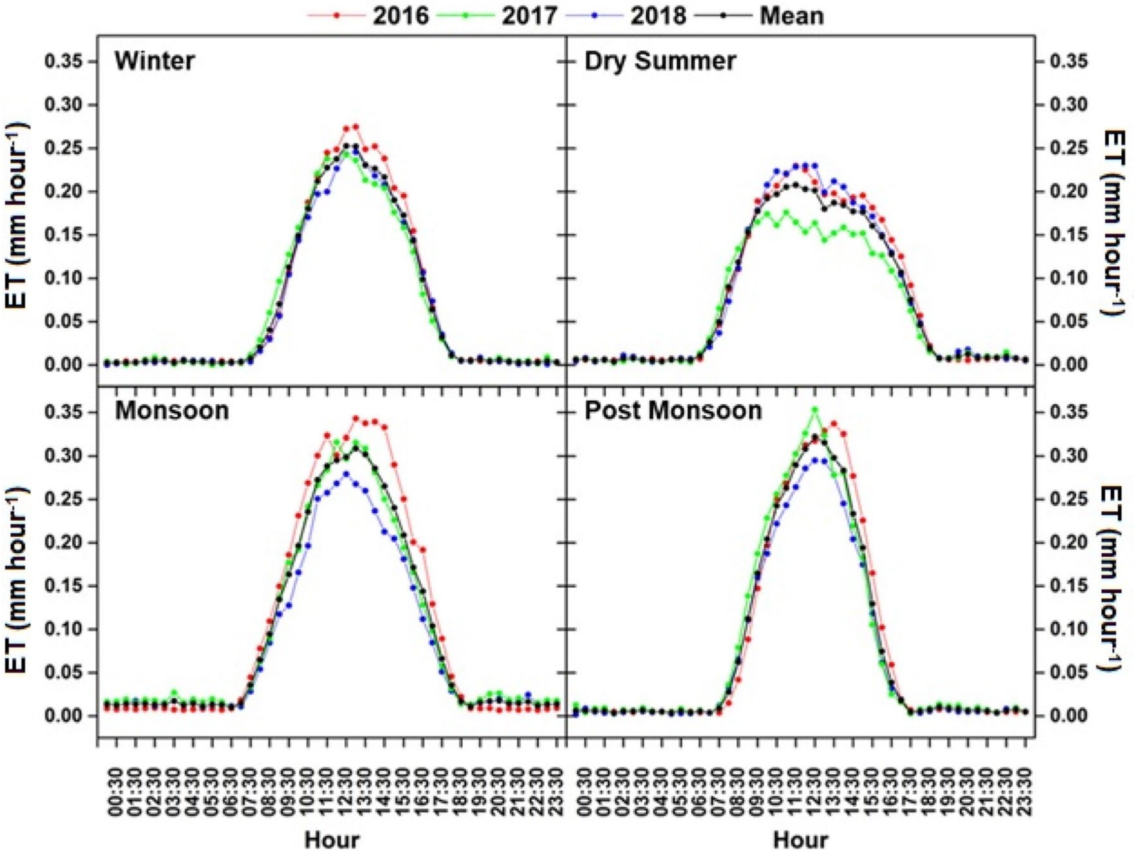


Fig. 4 Seasonal mean diurnal variation of evapotranspiration (ET, mm h^{-1})

post-monsoon season. These fluctuations were attributed to the presence of cloud cover. The trends observed in the daily ET values were very similar to the trend in R_g. From 2016 to 2018, the inter-annual mean T_{air} was 21.85 °C with a winter average of 16.10 °C and a summer average of 27.80 °C. The maximum value of T_{air} was observed in May in the dry summer season whereas the minimum T_{air} was observed during January in the winter season. The annual mean VPD was found to be 20.87 hPa. The seasonal means were found to be 17.38, 33.79, 16.62, and 15.68 hPa in winter, dry summer, monsoon, and post-monsoon seasons, respectively. The annual precipitation was 1115.40 mm. In 2017, the precipitation was 8.75% higher than the three-year average. The SWC varied slightly from season to season, apart from the monsoon season when the highest value of SWC was observed.

The RWA was carried out to understand the contribution of each biophysical variable in the variability of ET at the site scale. A combination of R_g, T_{air}, VPD, Precipitation, SWC, and LAI were able to explain 73% of the variability of ET. Amongst the biophysical variables used for the present analysis, R_g (rescaled relative weight (RRW) = 26.65) showed the highest control on the variability of ET, followed LAI (RRW = 22.26), VPD (RRW = 20.57), T_{air} (RRW = 17.85), SWC (RRW = 8.11), and precipitation (RRW = 4.57) (Fig. 7). It was found that R_g, LAI, T_{air}, and SWC had a positive relationship with the ET values, whereas VPD and precipitation had a negative correlation with ET. The lower relative weights of precipitation and SWC with respect to the variability in ET suggested that the ET in this ecosystem was not limited by water availability.

Discussion

The EC method facilitated the study of ET from half-hourly to yearly time scales by providing continuous time-series data for the study site. This method provides a direct measurement of energy fluxes (LE and H). The only problem is the gaps, which occur due to bad weather conditions and instrumental issues. Suitable gap-filling approaches were applied to obtain continuous time-series data of LE and H. To evaluate the performance of EC measurement at the present flux tower site, Watham et al. (2020) examined the energy balance closure for 2016–18 and reported a 73% closure.

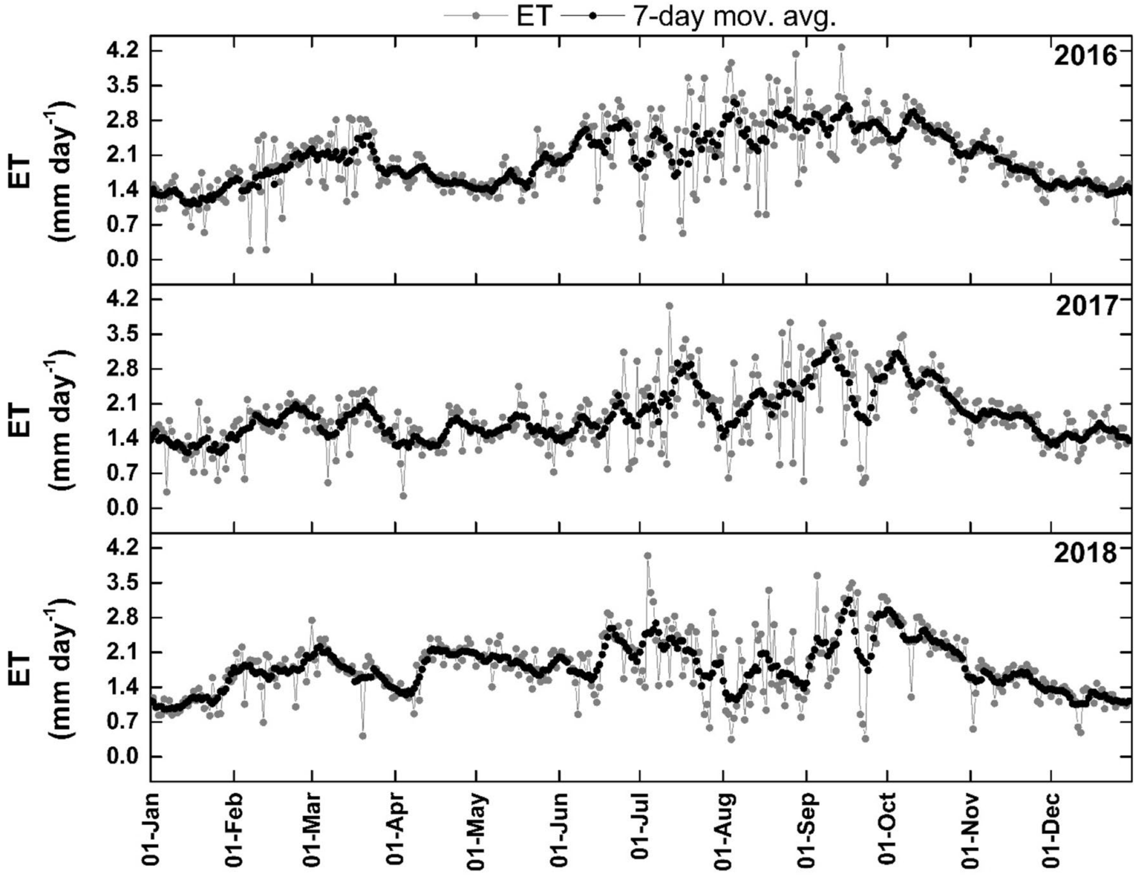


Fig. 5 Variation of daily evapotranspiration (ET) at Barkot flux site from 2016–2018

The diurnal and seasonal patterns of H were closely related to the pattern observed in R_g as the radiation is the principal energy source for daytime surface warming and evaporation (Grachev et al. 2020). The variability of LE is dependent on radiation as well as the availability of moisture. The lower value of LE in the dry summer season can be due to high temperature and low moisture conditions. In the monsoon season, more moisture is available in the ecosystem with enough sunshine, which leads to higher LE and ET. The stomatal openings are responsible for carbon fixation via photosynthesis as well as for water loss through transpiration. In the post-monsoon season, with moisture availability, warm temperature, and abundant sunlight, the optimum conditions for photosynthesis are available; hence, the LE and ET values were higher.

There is a dearth of ET studies on the forests of India; therefore, the results of the present study were compared to the forests with similar conditions. The mean annual ET of forests from across the globe has been reported to be 503 ± 388 mm year^{-1} (Baldocchi 2020). For the forests of China, in subtropical monsoon climate, the ET values of *Populus* sp. was found to be 957.8 mm year^{-1}, whereas, in subtropical monsoon humid climate, the ET values of an evergreen broadleaf forest was 630.0 mm year^{-1} (Xiao et al. 2013). The ET in *Populus* sp. was higher than that observed at BFS as the water demand of *Populus* sp. is higher than that of sal. The conditions at Chinese evergreen broadleaf forest in subtropical monsoon humid climate are close to the sal forest in monsoon-influenced subtropical climate at BFS. The difference in ET observed at both the sites can be attributed to the dynamics of LAI in sal forest as it shows slight deciduous behavior.

The variability in climate potentially influences the rates of ET from the forest canopies as these changes affect the surface conductance and transpiration (Humphreys et al. 2003). In dry conditions, the forests attained a physiological control of water loss by closing the stomata resulting in reduced canopy conductance whereas in water-saturated conditions the canopy conductance does not limit the water flux (Jarvis and McNaughton 1986). The biophysical variables play a vital role in controlling the ET dynamics through their possible effect may be site-specific (Yu et al. 2020).

In the present study, the RWA analysis reflected that R_g, LAI, T_{air}, and SWC had a positive influence on the ET values. However, VPD and precipitation had a negative influence on ET in this moist deciduous PFT. R_g has a strong

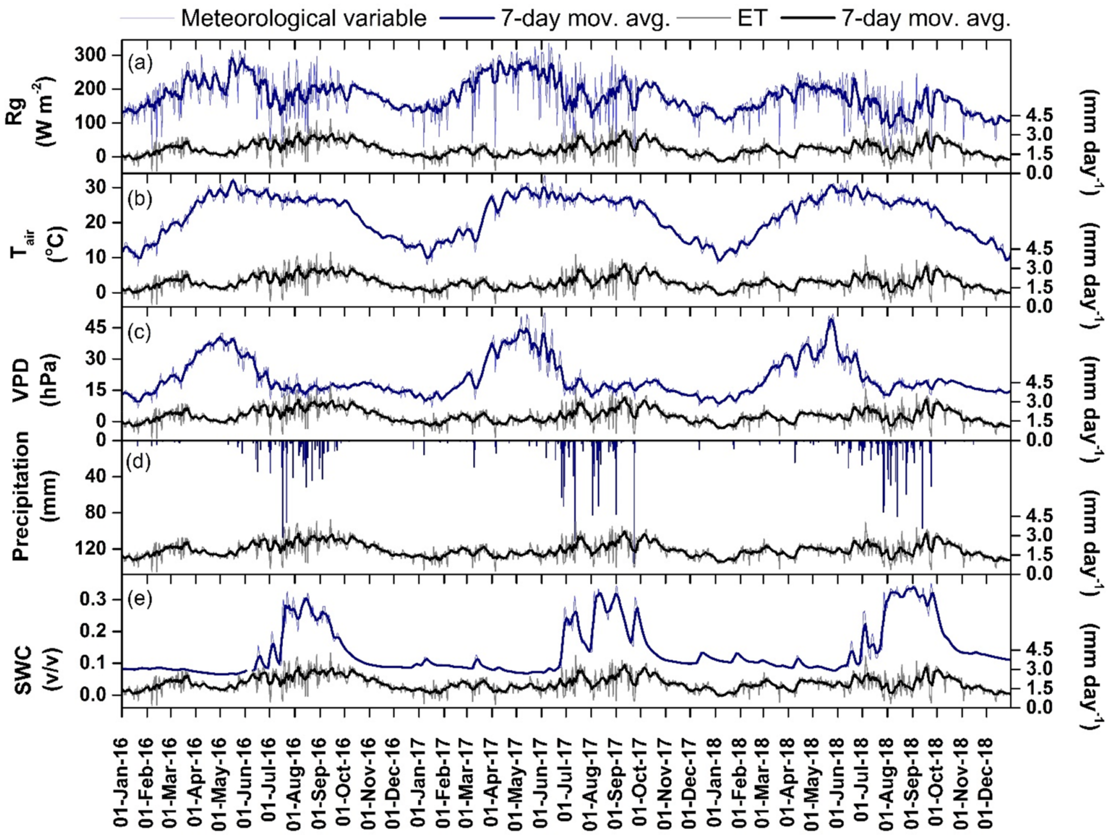
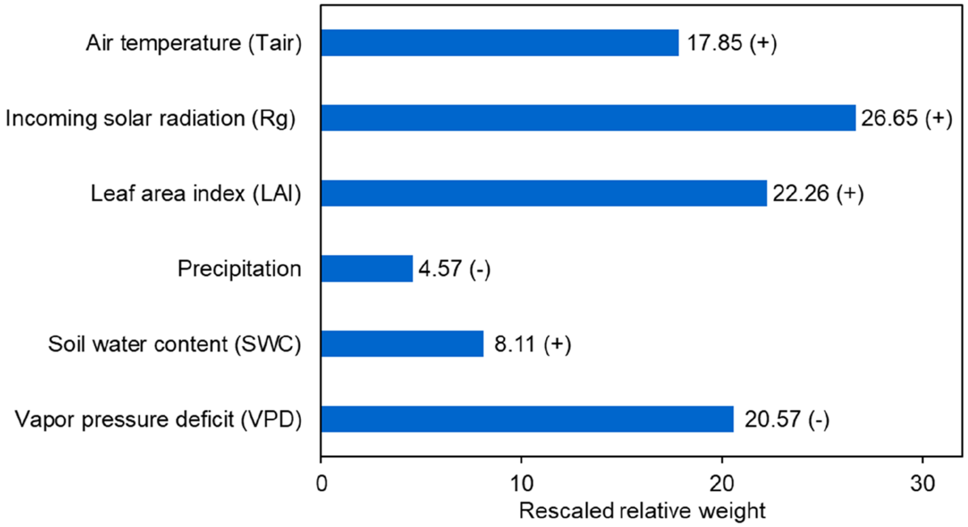


Fig. 6 Variation of daily meteorological variables **a** incoming solar radiation (R_g, W m^{-2}), **b** air temperature (T_{air}, °C), **c** vapour pressure deficit (VPD, hPa), **d** precipitation (mm), **e** soil water content (SWC, v/v) and evapotranspiration (ET, mm day^{-1}) from 2016 to 2018

Fig. 7 Rescaled relative weight of various biophysical variables on evapotranspiration (the signs represent the type of relationship)



positive influence on the ET values, as it is the only input energy, which after partitioning can affect the heat and water vapour transport to and from the leaf surfaces (Oke 1987). The negative influence of VPD on ET variability can be attributed to the self-adaptive behavior shown by the plants to reduce the utilization of resources by closing the stomata to conserve water. The seasonality of ET can be affected by LAI as it provides the surface for transpiration to take place and precipitation interception by the canopy (Jin et al. 2017), which may result in an increase in

ET. Singh et al. (2014) also reported that the relationship between ET and LAI showed tight seasonal coupling. As reported in the study, the temperature was also found to have a significant role in controlling the variability of ET (Xiao et al. 2013; Yu et al. 2020). An optimum temperature is required for photosynthesis to take place, which in turn controls the transpiration process from leaf stomata. Both the processes are intrinsically related in terrestrial ecosystems (Jarvis 1976). The temperature also influences the evaporation process in an ecosystem. Precipitation can encourage ET by increasing SWC (Legesse et al. 2003) and promoting vegetation growth (Jin et al. 2017). On the other hand, precipitation can sometimes limit ET by reducing radiation due to cloudy conditions (Yu et al. 2020). In the present study, the impact of precipitation on ET was found to be negative, which indicates that the ET in moist deciduous PFT is not water-limited. Whereas it is positively correlated with R_g and T_{air}, which reveals that it is energy-limited. A combination of these variables was able to give an insight into the biophysical controls on the variability of ET of the moist deciduous PFT present at BFS. With an increase in temperature and atmospheric CO_2 in view of climate change, it is very difficult to predict the behavior of ecosystem ET. With the increase in temperature, the evaporation may increase, however, the greater CO_2 concentration and increase in VPD may lead to stomatal closure, which will result in reduced transpiration (Baldocchi 2020). Therefore, such long-term ET measurements can be crucial for understanding the role of forests in the changing climate.

Conclusion

The forests are an intrinsic part of the terrestrial hydrological cycle. EC method has been considered as one of the most reliable techniques to investigate the carbon, water, and energy fluxes and to understand the biophysical controls in their variability by providing continuous, long-term observations for these complex processes. ET provides a nexus between these complex processes. Hence, it is essential to get accurate estimates of ET to decode the trade-off between these processes and to perceive the hydrological cost of the carbon sequestration process. This study presented comprehensive estimates of ET using the EC flux tower measurements for a period from 2016 to 2018 and also provided an insight into the biophysical controls on ET in moist deciduous PFT of NWH foothills of India. The average annual ET was found to be 693.67 ± 46.70 mm year^{-1}. The highest seasonal ET was found in the post-monsoon season. R_g, LAI, and VPD primarily controlled the variation in ET. The study provides the first direct, long-term estimates of ET for an Indian forest.

Acknowledgements The present study was carried out as a part of Soil-Vegetation-Atmosphere-Flux (SVAF) of National Carbon Project (NCP) supported by ISRO-Geosphere-Biosphere Programme. The authors wish to acknowledge the Divisional Forest Officer, Dehradun Forest Division and staff of Barkot Forest Range, Dehradun Forest Division, Government of Uttarakhand, India, and field staff of Barkot Flux Site for field support. Thanks are also due to the anonymous reviewers for their valuable suggestions, which helped us to improve the manuscript.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56. FAO Rome 300(9):D05109

Anderson MC, Hain C, Otkin J, Zhan X, Mo K, Svoboda M, Wardlow B, Pimstein A (2013) An intercomparison of drought indicators based on thermal remote sensing and NLDAS-2 simulations with US Drought Monitor classifications. J Hydrometerol 14(4):1035–1056. https://doi.org/10.1175/JHM-D-12-0140.1

Anderson MC, Kustas WP, Norman JM, Hain CR, Mecikalski JR, Schultz L, González-Dugo MP, Cammalleri C, d'Urso G, Pimstein A, Gao F (2011) Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. Hydrol Earth Syst Sci 15:223

Aubinet M, Vesala T, Papale D (2012) Eddy covariance: a practical guide to measurement and data analysis. Springer, Dordrecht, p 438

Baldocchi DD (2020) How eddy covariance flux measurements have contributed to our understanding of Global Change Biology. Glob Change Biol 26(1):242–260. https://doi.org/10.1111/gcb.14807

Baldocchi DD, Ryu Y (2011) A synthesis of forest evaporation fluxes–from days to years–as measured with eddy covariance. In: Levia D, Carlyle-Moses D, Tanaka T (eds) Forest hydrology and biogeochemistry ecological studies (analysis and synthesis), vol 216. Springer, Dordrecht, pp 101–116

Baldocchi DD, Xu L (2007) What limits evaporation from Mediterranean oak woodlands—the supply of moisture in the soil, physiological control by plants or the demand by the atmosphere? Adv Water Res 30(10):2113–2122. https://doi.org/10.1016/j.advwatres.2006.06.013

Baldocchi DD, Xu L, Kiang N (2004) How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak–grass savanna and an annual grassland. Agric For Meteorol 123(1–2):13–39. https://doi.org/10.1016/j.agrformet.2003.11.006

Burba G (2013) Eddy Covariance method for scientific industrial agricultural and regulatory applications: a field book on measuring ecosystem gas exchange and areal emission rates. LI-COR Biosciences, Lincoln, p 331

Champion SH, Seth SK (1968) A revised survey of the forest types of India. Manager of Publications, Delhi

Deb Burman PK, Sarma D, Williams M, Karipot A, Chakraborty S (2017) Estimating gross primary productivity of a tropical forest ecosystem over north-east India using LAI and meteorological variables. J Earth Syst Sci 126(7):99. https://doi.org/10.1007/s12040-017-0874-3

Dunne T, Zhang W, Aubry BF (1991) Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resour Res 27(9):2271–2285. https://doi.org/10.1029/91WR01585

Foltýnová L, Fischer M, McGloin RP (2020) Recommendations for gap-filling eddy covariance latent heat flux measurements using marginal distribution sampling. Theo Appl Climatol 139(1):677–688. https://doi.org/10.1007/s00704-019-02975-w

Ford CR, Hubbard RM, Kloeppel BD, Vose JM (2007) A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. Agric For Meteorol 145(3–4):176–185. https://doi.org/10.1016/j.agrformet.2007.04.010

Grachev AA, Fairall CW, Blomquist BW, Fernando HJ, Leo LS, Otárola-Bustos SF, Wilczak JM, McCaffrey KL (2020) On the surface energy balance closure at different temporal scales. Agric For Meteorol 281:107823. https://doi.org/10.3390/atmos11111160

Greve P, Orlowsky B, Mueller B, Sheffield J, Reichstein M, Seneviratne SI (2014) Global assessment of trends in wetting and drying over land. Nat Geosci 7(10):716–721. https://doi.org/10.1038/ngeo2247

Hamon WR (1960) Estimating potential evapotranspiration. Dissertation, Massachusetts Institute of Technology, Massachusetts, USA

Herbst M, Rosier PT, McNeil DD, Harding RJ, Gowing DJ (2008) Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. Agric For Meteorol 148(11):1655–1667. https://doi.org/10.1016/j.agrformet.2008.05.011

Humphreys ER, Black TA, Ethier GJ, Drewitt GB, Spittlehouse DL, Jork EM, Nesic Z, Livingston NJ (2003) Annual and seasonal variability of sensible and latent heat fluxes above a coastal Douglas-fir forest, British Columbia, Canada. Agric For Meteorol 115(1–2):109–125. https://doi.org/10.1016/S0168-1923(02)00171-5

Jarvis PG (1976) The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philos Trans R Soc Lond B 273(927):593–610. https://doi.org/10.1098/rstb.1976.0035

Jarvis PG, McNaughton KG (1986) Stomatal control of transpiration: scaling up from leaf to region. Adv Ecol Res 15:1–49. https://doi.org/10.1016/S0065-2504(08)60119-1

Jha CS, Thumaty KC, Rodda SR, Sonakia A, Dadhwal VK (2013) Analysis of carbon dioxide, water vapour and energy fluxes over an Indian teak mixed deciduous forest for winter and summer months using eddy covariance technique. J Earth Syst Sci 122:1259–1268

Jin Z, Liang W, Yang Y, Zhang W, Yan J, Chen X, Li S, Mo X (2017) Separating vegetation greening and climate change controls on evapotranspiration trend over the Loess Plateau. Sci Rep 7(1):1–15. https://doi.org/10.1038/s41598-017-08477-x

Johnson JW (2000) A heuristic method for estimating the relative weight of predictor variables in multiple regression. Multivar Behav Res 35(1):1–19

Legesse D, Vallet-Coulomb C, Gasse F (2003) Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. J Hydrol 275(1–2):67–85. https://doi.org/10.1016/S0022-1694(03)00019-2

Ma X, Feng Q, Su Y, Yu T, Jin H (2017) Forest evapotranspiration and energy flux partitioning based on eddy covariance methods in an arid desert region of northwest China. Adv Meteorol. https://doi.org/10.1155/2017/1619047

Mao J, Fu W, Shi X, Ricciuto DM, Fisher JB, Dickinson RE, Wei Y, Shem W, Piao S, Wang K, Schwalm CR (2015) Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends. Environ Res Lett 10(9):094008. https://doi.org/10.1088/1748-9326/10/9/094008

Marques TV, Mendes K, Mutti P, Medeiros S, Silva L, Perez-Marin AM, Campos S, Lúcio PS, Lima K, dos Reis J, Bezerra B (2020) Environmental and biophysical controls of evapotranspiration from Seasonally Dry Tropical Forests (Caatinga) in the Brazilian Semiarid. Agric For Meteorol 287:107957. https://doi.org/10.1016/j.agrformet.2020.107957

Monteith JL (1965) Evaporation and environment. Symposia of the Society for Experimental Biology, vol 19. Cambridge University Press, Cambridge, pp 205–234

Nandy S, Saranya M, Srinet R (2021) Spatio-temporal variability of water use efficiency and its drivers in major forest formations in India. Remote Sens Environ. https://doi.org/10.1016/j.rse.2021.112791

Nandy S, Singh R, Ghosh S, Watham T, Kushwaha SPS, Kumar AS, Dadhwal VK (2017) Neural network-based modelling for forest biomass assessment. Carbon Manag 8(4):305–317. https://doi.org/10.1080/17583004.2017.1357402

Oke TR (1987) Boundary layer climates. Methuen, London and New York

Otkin JA, Anderson MC, Hain C, Svoboda M, Johnson D, Mueller R, Tadesse T, Wardlow B, Brown J (2016) Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. Agric For Meteorol 218:230–242. https://doi.org/10.1016/j.agrformet.2015.12.065

Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A, Grünwald T (2005) On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob Change Biol 11(9):1424–1439. https://doi.org/10.1111/j.1365-2486.2005.001002.x

Roberts JM (2009) The role of forests in the hydrological cycle. In: Roberts JM, Lund HG (eds) Forests and forest plants, vol III. Centre for Forest Biology, University of Victoria, Victoria, pp 42–76

Rodda SR, Thumaty KC, Jha CS, Dadhwal VK (2016) Seasonal variations of carbon dioxide, water vapor and energy fluxes in tropical Indian mangroves. Forests 7(2):35. https://doi.org/10.3390/f7020035

Schwärzel K, Menzer A, Clausnitzer F, Spank U, Häntzschel J, Grünwald T, Köstner B, Bernhofer C, Feger KH (2009) Soil water content measurements deliver reliable estimates of water fluxes: a comparative study in a beech and a spruce stand in the Tharandt forest (Saxony, Germany). Agric For Meteorol 149(11):1994–2006. https://doi.org/10.1016/j.agrformet.2009.07.006

Sheffield J, Wood EF, Munoz-Arriola F (2010) Long-term regional estimates of evapotranspiration for Mexico based on downscaled ISCCP data. J Hydrometeorol 11(2):253–275. https://doi.org/10.1175/2009JHM1176.1

Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491(7424):435–438. https://doi.org/10.1038/nature11575

Singh N, Patel NR, Bhattacharya BK, Soni P, Parida BR, Parihar JS (2014) Analyzing the dynamics and inter-linkages of carbon and water fluxes in subtropical pine (Pinus roxburghii) ecosystem. Agric For Meteorol 197:206–218. https://doi.org/10.1016/j.agrformet.2014.07.004

Soubie R, Heinesch B, Granier A, Aubinet M, Vincke C (2016) Evapotranspiration assessment of a mixed temperate forest by four methods: eddy covariance, soil water budget, analytical and model. Agric For Meteorol 228:191–204. https://doi.org/10.1016/j.agrformet.2016.07.001

Srinet R, Nandy S, Patel NR (2019) Estimating leaf area index and light extinction coefficient using Random Forest regression algorithm in a tropical moist deciduous forest, India. Ecol Inform 52:94–102. https://doi.org/10.1016/j.ecoinf.2019.05.008

Srinet R, Nandy S, Padalia H, Ghosh S, Watham T, Patel NR, Chauhan P (2020) Mapping plant functional types in northwest Himalayan foothills of India using random forest algorithm in google earth engine. Int J Remote Sens 41(18):7296–7309. https://doi.org/10.1080/01431161.2020.1766147

Tong X, Zhang J, Meng P, Li J, Zheng N (2017) Environmental controls of evapotranspiration in a mixed plantation in North China. Int J Biometeorol 61(2):227–238. https://doi.org/10.1007/s00484-016-1205-0

Vincke C, Breda N, Granier A, Devillez F (2005) Evapotranspiration of a declining *Quercus robur* (L.) stand from 1999 to 2001 I Trees and forest floor daily transpiration. Ann For Sci 62(6):503–512. https://doi.org/10.1051/forest:2005055

Wang K, Dickinson RE (2012) A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability. Rev Geophys. https://doi.org/10.1029/2011RG000373

Watham T, Kushwaha SPS, Patel NR, Dadhwal VK, Kumar AS (2017a) Ecosystem productivity and its response to environmental variable of moist Indian sal forest. Trop Ecol 58(4):761–768

Watham T, Patel NR, Kushwaha SPS, Dadhwal VK (2017b) A study on sap flow rate of Mallotus philippensis and its relationship with environmental factors. J Agrometeorol 19(2):104–109

Watham T, Srinet R, Nandy S, Padalia H, Sinha SK, Patel NR, Chauhan P (2020) Environmental control on carbon exchange of natural and planted forests in Western Himalayan foothills of India. Biogeochemistry. https://doi.org/10.1007/s10533-020-00727-x

Wever LA, Flanagan LB, Carlson PJ (2002) Seasonal and interannual variation in evapotranspiration, energy balance and surface conductance in a northern temperate grassland. Agric For Meteorol 112(1):31–49. https://doi.org/10.1016/S0168-1923(02)00041-2

Wilson KB, Baldocchi DD (2000) Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. Agric For Meteorol 100(1):1–18. https://doi.org/10.1016/S0168-1923(99)00088-X

Wutzler T, Lucas-Moffat A, Migliavacca M, Knauer J, Sickel K, Šigut L, Menzer O, Reichstein M (2018) Basic and extensible post-processing of eddy covariance flux data with REddyProc. Biogeoscience 15(16):5015–5030. https://doi.org/10.5194/bg-15-5015-2018

Xiao J, Sun G, Chen J, Chen H, Chen S, Dong G, Gao S, Guo H, Guo J, Han S, Kato T (2013) Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China. Agric For Meteorol 182:76–90. https://doi.org/10.1016/j.agrformet.2013.08.007

Yu D, Li X, Cao Q, Hao R, Qiao J (2020) Impacts of climate variability and landscape pattern change on evapotranspiration in a grassland landscape mosaic. Hydrol Process 34(4):1035–1051. https://doi.org/10.1002/hyp.13642

Zha T, Li C, Kellomäki S, Peltola H, Wang KY, Zhang Y (2013) Controls of evapotranspiration and CO2 fluxes from scots pine by surface conductance and abiotic factors. PLoS ONE 8(7):e69027. https://doi.org/10.1371/journal.pone.0069027