APPENDICES

APPENDIX

A. Research paper published in journals from the thesis:

1. **Sarma, D.**, Baruah, K.K., Baruah, R., Gogoi, N., Bora, A., Chakraborty, S., and Karipot, A. Carbon dioxide, water vapour and energy fluxes over a semi-evergreen forest in Assam, Northeast India. *Journal of Earth System Science,* 127:94, 2018.
2. **Sarma, D.**, Baruah, K. K., Chakraborty, S., Karipot, A., and Baruah, R. Impact of ecosystem respiration on carbon balance in a semi evergreen forest of Northeast India. *Current Science*, 2018, (accepted).

B. Research papers presented at seminars and conferences:

1. **Sarma, D.** Baruah K. K., Gogoi, N., Baruah, R., Chakraborty, S., and Karipot, A. Carbon dioxide flux from a semi evergreen forest in Assam, India using eddy covariance technique. Asia Flux Conference, IITM, Pune, India from 25 to 27th November, 2015.

2. **Sarma, D.,** Bora, A., and Gorh, D. Seasonal changes in CO_2 and energy fluxes over a semi evergreen forest of Kaziranga National Park, Assam, India. National Seminar on Climate Change and Society, Tezpur University, Assam, India from 24-25th February, 2017.

C. Other publications:

1. Sinha, N., Chakraborty, S., Chattopadhyay, R., Goswami, B. N., Mohan, P. M., Parua, D. K., **Sarma, D.**, Datye, A., Sengupta, S., Bera, S., Baruah, K. K. Isotopic investigation of the moisture transport processes over the Bay of Bengal, 2019. *Journal of Hydrology*, (accepted).

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Carbon dioxide, water vapour and energy fluxes over a semi-evergreen forest in Assam, Northeast India

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The eddy covariance method is a powerful technique for quantification of CO_2, H_2O and energy fluxes in natural ecosystems. Leaf area index (LAI) and its changes are significant drivers of CO_2 and H_2O exchange in a forest ecosystem due to their role in photosynthesis. The present study reports the seasonal variation of CO_2 and energy fluxes and their relationship with other meteorological parameters of a semi-evergreen primary forest of Kaziranga National Park, Assam, India during February 2016–January 2017. The diurnal pattern of half hourly average CO_2 fluxes over the forest was found to be mostly dominated by the incident photosynthetically active radiation. During the period of study, diurnal variations of CO_2 flux showed a maximum value of $-9.97\,\mu\text{mol m}^{-2}\text{s}^{-1}$ in the month of June during summer which is also the beginning of the monsoon season. The monthly averaged diurnal CO_2 flux and variation in LAI of the forest canopy closely followed each other. The annual net ecosystem exchange of the forest estimated from the CO_2 flux data above the canopy is 84.21 g C $\text{m}^{-2}\,\text{yr}^{-1}$. Further studies are in progress to confirm these findings. The estimated average annual evapotranspiration of the semi-evergreen forest is 2.8 ± 0.19 mm day^{-1}. The study of partitioning of energy fluxes showed the dominance of latent heat fluxes over sensible heat fluxes. The energy balance closure was found to increase with an increase in instability and the highest closure of around 83% was noted under neutral conditions.

Keywords. Eddy covariance; semi-evergreen forest; surface energy balance; carbon dioxide flux; Indian subcontinent.

1. Introduction

The rising trend of carbon dioxide (CO_2) concentration is considered to be one of the major threats to the earth–atmosphere system due to its imminent impact on global warming. Kyoto protocol highlighted the need for identification and quantification of sources and sinks of CO_2 in parallel with the formation of policies for emission reduction (Kowalski *et al.* 2008). A systematic monitoring of global changes in the terrestrial biosphere has become an important activity because of increasing impacts of human on biological systems and atmosphere (Running *et al.* 1999). Forests are considered to be a major terrestrial sink of carbon, hence an important component of

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the global carbon cycle (Heinemeyer *et al.* 2007). The terrestrial C sink is reported to be about 2.6 PgC in 2010, but has a high inter-annual variability (Lorenz 2013). The role of forest ecosystems around the globe is very critical and is responsible for about half of the total terrestrial gross primary production which is reported to be 123 PgC yr^{-1} (Lorenz 2013). Carbon balance studies in forests and agricultural ecosystems are major ongoing research activity worldwide. The long-term and continuous monitoring of CO_2 fluxes over the ecosystems are necessary for the estimation of the annual budget of CO_2 exchange.

The eddy covariance (EC) method has evolved as a standard and defensible tool for the ecosystem scientists for the measurement of the biosphere–atmosphere exchange of trace gases and energy fluxes across the time spectrum of the operation of the biosphere (Baldocchi *et al.* 2001). The EC is the most preferred one among the other flux measurement techniques due to its proficiency in the real-time quantification of fluxes starting from hours to several years, representing the extensive area of land continuously without disturbing the ecosystem. In the EC technique, flux computation is done as the covariance between the vertical velocity fluctuations and fluctuations in the concentration of trace gases in the atmosphere. Flux measurements in the forest ecosystem have been carried out in many sites across the world, but relatively very few studies have been conducted in the Indian subcontinent. However, Jha *et al.* (2013) have measured CO_2, water vapour and energy fluxes in a teak mixed deciduous forest in central India during 2011 and 2012 using the EC technique. The EC data were also used by Watham *et al.* (2014) to study the monthly and annual variations of CO_2 and H_2O fluxes over a mixed forest plantation in Terai central forest division, Uttarakhand, India. Rodda *et al.* (2016) also used the EC technique for the estimation of net ecosystem exchange (NEE) of CO_2 and the quantification of energy and water vapour fluxes in Mangrove ecosystems, Sundarbans (India). The above observations are unlikely to be representative of other Indian ecosystems because of their different geographical context, climatic regime and diverse vegetation pattern.

As a result, the nature of carbon and energy fluxes over a variety of ecosystems over the region remains to be poorly understood. The Indian forest is believed to be a net sink of CO_2 (Lal *et al.* 2000), but the nature of variation on relatively short temporal and spatial scales may vary considerably. The northeastern part of India is endowed with a rich and varied biophysical environment because of its unique geographical location in the extreme northeast corner of the Indian subcontinent. A relatively greater distance from the main land, poor communication facilities, vast mountainous terrain, dense forests, heavy rainfall, wetlands and frequent floods have created a geographical remoteness of this area. It is essential to quantify the ecosystem CO_2 fluxes of forest ecosystems of this region to better understand the carbon dynamics. To fulfil this objective, the Ministry of Earth Science, Government of India, has taken an initiative to establish a greenhouse gas flux observational network (Metflux India) across the country. Within this framework, the Tezpur Central University at Tezpur located at the northeastern state of Assam in association with the Indian Institute of Tropical Meteorology, Pune has established an EC-based flux tower observational site at a semi-evergreen primary forest of Kaziranga National Park (KNP), Assam, famous for the great one horned rhinoceros. The study is first of its kind in this northeastern part of India. The establishment of the tower in such a remote and difficult to approach site at KNP deserves special attention from the meteorologists and environmental scientists of the globe. The primary objective of the present study was to monitor the exchange of CO_2, H_2O and energy between the forest (KNP) and the atmosphere from February 2016 to January 2017 as well as to identify the environmental factors that control the exchange processes.

2. Materials and methods

2.1 *Experimental site*

A flux tower was installed at the KNP in Nagaon district of Assam, India (figure 1). The tower is located at 26°34′48″N latitude and 93°6′28″E longitude and at a distance of 55 km from the Tezpur University. The floristic composition of the park can be divided into the following forest types and biomes (Champion and Seth 1968), namely eastern wet alluvial grasslands, Assam alluvial plains semi-evergreen forests, tropical moist mixed deciduous forests, Eastern Dillenia swamp forests, wetlands and sandy ‘chars’. The climate of the area can be classified as humid sub-tropical according to the Köppen climate classification. The tower is

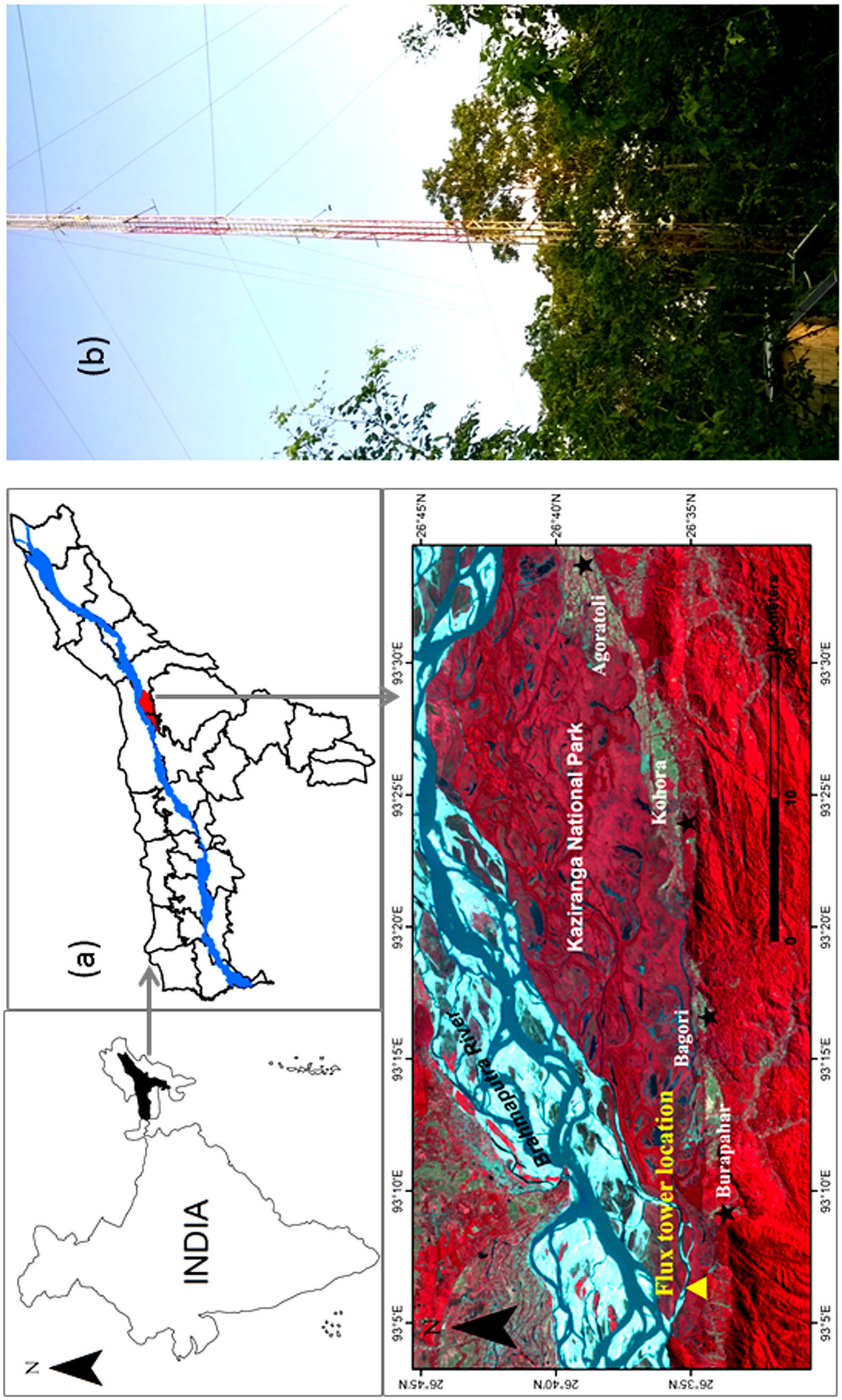

Figure 1. (**a**) Location map of the study area and (**b**) photograph of the tower.

Table 1. *List of sensors and accessories.*

Sensors/accessories	Height/depth (m)	Model/manufacturer
(a)With fast response		
3D sonic anemometer–thermometer	37	Wind Master Pro, Gill Instruments, UK
CO_2–H_2O enclosed path analyser	37	LI-7200, LI-COR, USA
Data logger (analyser interface unit)	36	LI-7550, LI-COR, USA
Flow module	36	7200-101, LI-COR, USA
(b) With slow response		
Four component net radiometer	24 m	NR01, Hukseflux
Multicomponent weather sensor	8 and 36 m	WXT520, Vaisala Oyj
PAR sensor	24 m	SQ-100 and 300 series, Apogee instruments
Soil heat flux plate	5 cm	HFP01SC-20, Hukseflux
Data logger	3 m	CR3000, Campbell Scientific

located on a relatively flat terrain and the type of vegetation around the tower is semi-evergreen. The park receives a total annual rainfall of 2220 mm and the mean annual temperature recorded over the region is 23°C. Measurements were carried out using the fast and slow response sensors. The list of sensors used in the study is given in table 1(a and b).

2.2 *EC measurement*

CO_2, H_2O and energy fluxes have been measured using the EC technique at the KNP from early 2015. The average height of the canopy around the tower is 20 m and the EC system (table 1a) including a three-dimensional (3D) sonic anemometer–thermometer and a CO_2–H_2O enclosed path analyser was installed at a height of 37 m on the 50 m tall tower.

Vertical flux computation in this study was carried out by following the method proposed by Baldocchi *et al.* (1988) as:

$$F_{\mathrm{v}} = \overline{\rho_{\mathrm{d}} w s},$$

where F_{v} is the vertical flux, ρ_{d} is the density of air, w is the vertical component of wind speed, s is the mixing ratio of the substance of interest and overbar indicates the mean. Assuming the air density fluctuations to be zero and mean vertical flow to be negligible, the above equation can be presented as:

$$F_{\mathrm{v}} = \overline{\rho_{\mathrm{d}}}\,\overline{w' s'}.$$

In the above equation, instantaneous deviation from the mean is indicated by the prime symbol.

2.3 *Meteorological and soil measurements*

In parallel to fast measurements, the slow response sensors (table 1b) were also installed at the site for the measurement of meteorological parameters. A net radiometer was installed for the measurement of four components of radiation. Multicomponent weather sensors were used for the measurement of air temperature, rainfall, relative humidity, wind speed, etc. The tower has been equipped to measure photosynthetically active radiation (PAR) with the help of a PAR sensor. Soil heat flux plates were used for the measurement of soil heat flux.

2.4 *Leaf area index (LAI)*

LAI, a quantitative indicator of canopy architecture (Borah and Baruah 2016), was measured within a radius of 100 m around the tower by using the plant canopy analyser (LI-2200, LI-COR Inc., USA) at biweekly intervals. For the LAI measurement, three above canopy and 15 below canopy readings were taken from different locations around the tower using the optical sensor LI-2200. The internal software of the data logger automatically computes the LAI from the above and below canopy readings using the theory of light interception at five zenith angles by the canopy.

2.5 *Data processing*

2.5.1 *Primary raw data processing*

Flux computation was carried out by using the software EddyPro (version 6.2.0, LI-COR, USA) and was averaged for 30 min. The processing of raw data includes corrections for wind measurement offsets of the anemometer, viz., the angle of attack correction for wind components and any tilt in the anemometer were compensated by the double rotation method (Kaimal and Finnigan 1994). The detrending of the time series was done by the block averaging method, time lag between the anemometer and LI-7200 was compensated by the covariance maximisation method. Statistical tests for raw data screening were carried out by the methods of Vickers and Mahrt (1997) which include spike count/removal, amplitude resolution, drop outs, absolute limits, skewness and kurtosis. Spectral correction steps for the low-frequency range include analytic correction of high-pass filtering effects (Moncrieff *et al.* 2004) and for the high-frequency range include correction of low-pass filtering effects as referred by Moncrieff *et al.* (1997).

2.5.2 *Secondary CO_2 flux spike removal*

Despite the standard corrections used in EddyPro software, the processed data still had some unrealistic spikes which were removed before computing the fluxes. Those spikes would have occurred due to some non-localised advection events or other non-stationary phenomena (Rodda *et al.* 2016). We used a statistical approach similar to that used by Thomas *et al.* (2011) for detecting and removing unrealistic spikes in the data set and about 13% of such data were removed.

2.5.3 *Removal of negative night-time CO_2 fluxes*

The processed data contains some negative night-time fluxes of CO_2 which may occur in the forests under the stable atmospheric conditions. Such unrealistic negative fluxes (≈12%), which occurred when global solar radiation (measured by using a four-component net radiometer) was <20 W m^{-2}, were detected and removed from the dataset.

2.5.4 *Friction velocity correction, gap filling and uncertainty of filled data*

During the night-time due to the weak atmospheric turbulence and stable air stratification, the EC system underestimates CO_2 fluxes. We used REddyProcWeb online tool of the Department of Biogeochemical Integration of Max Planck Institute for Biogeochemistry (https://www.bgc-jena.mpg.de/REddyproc/brew/REddyproc.rhtml) for friction velocity filtering and gap filling of flux data, which uses the moving point test for u^* threshold estimation suggested by Papale *et al.* (2006). In our study, the annual u^* threshold estimated by the online tool is 0.37 m s^{-1} and a total of 33% of data were removed from the available dataset and gap filled. The root mean square error of the gap filled CO_2 flux is 2.73 ± 0.27 μmol m^{-2} s^{-1}.

3. Results and discussion

3.1 *Variations in meteorological conditions and LAI*

In the present study, we considered four distinct seasons of the year such as winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). The diurnal variations of the monthly mean of various meteorological parameters around the study area during the period February 2016–January 2017 are presented in figure 2(a–d). The diurnal variations of air temperature (figure 2a) crossed 32°C in August 2016 during summer and a lower temperature of around 13°C was observed in the month of January 2017 during winter. The lowest humidity (figure 2b) around 40% was observed in January 2017 during winter and it increased up to 90% in the month of October during autumn. Variation in wind speed (figure 2c) above the canopy showed high values in the month of April and it ranged from 0.5 to 4.2 m s^{-1} throughout the period of study. The highest rainfall of 384 mm was received at the site in the month of April 2016 (figure 2d) due to the effect of Nor'westers, which establishes over northeast India from March up to May, i.e., until the beginning of monsoon (Mahanta *et al.* 2013). Monsoon (during June, July, August and September) contributed 55% of the total rainfall at the site.

During the night-time, net radiation (figure 3) was observed to be negative due to the dominance of the outgoing component of long-wave radiation from the surface than the other components, it started to attain positive values between 05:00 and 06:30 hrs depending upon seasonal shift in sunrise time and reaching its peak at noon to early afternoon hours. The diurnal peak of net radiation was in the range of 431–639 W m^{-2} between February and August. PAR also followed the same diurnal pattern as net radiation during the daytime, with a maximum PAR of 1542 μmol m^{-2} s^{-1} observed in the month of August in the noon hours (figure 3).

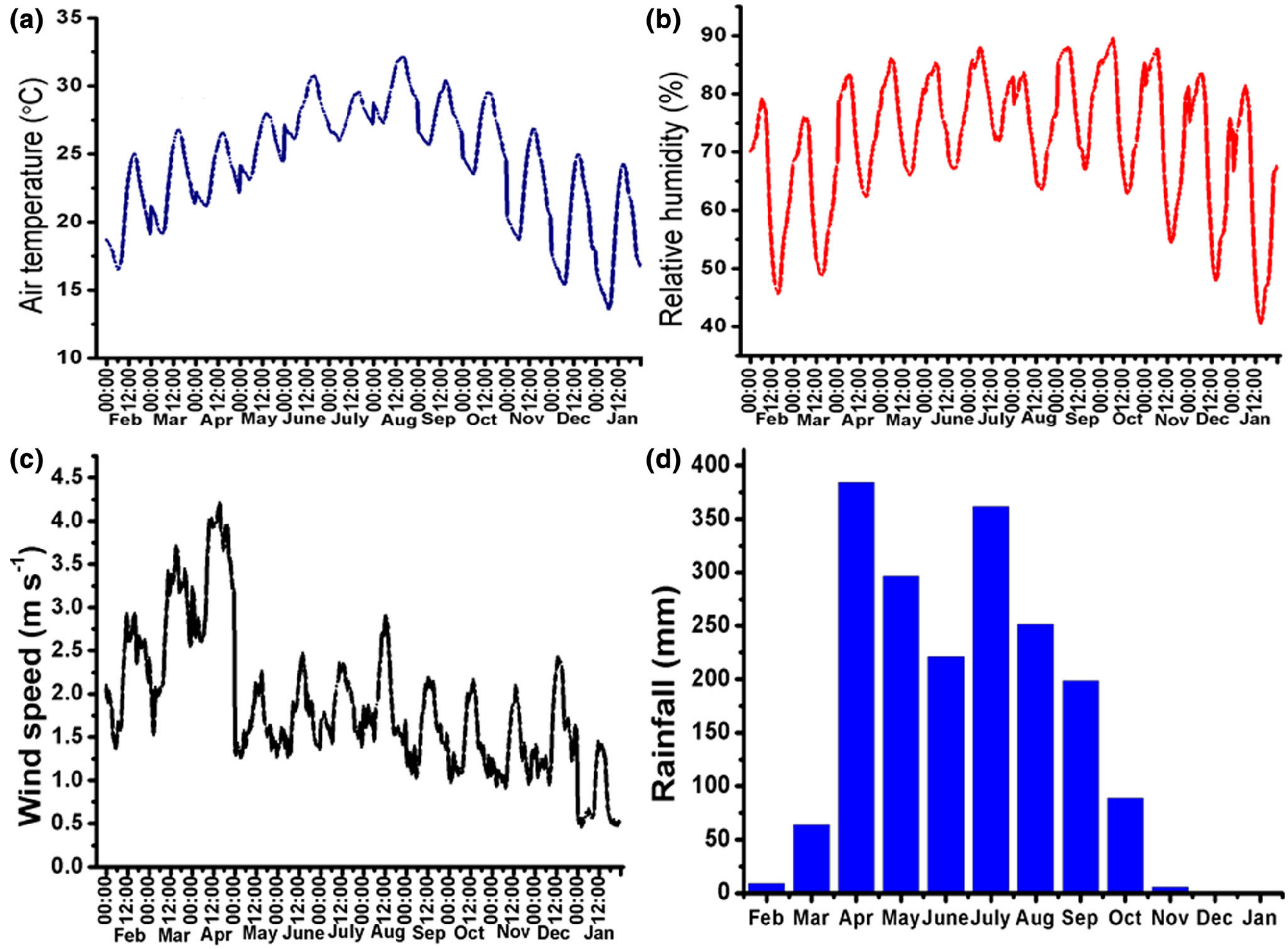

Figure 2. (**a**) Diurnal variations of air temperature (monthly mean) from February 2016 to January 2017, (**b**) diurnal variations of relative humidity (monthly mean) from February 2016 to January 2017, (**c**) diurnal variations in wind speed (monthly mean) from February 2016 to January 2017, and (**d**) monthly total rainfall recorded in the study area from February 2016 to January 2017.

The LAI, which is the quantitative descriptor of leaf amount and biological productivity (Hutchison *et al.* 1986; Chen *et al.* 1997), has shown a continuously increasing trend from early January (0.76) to a peak of 3.25 in the month of June and decreased to 1.85 towards the end of October. In winter, due to dry conditions and low air temperature, the LAI of the forest was low, which started to increase slowly from March due to the increase in air temperature and starting of rain (Ellis and Hatton 2008). The beginning of the spring season and the end of summer coincide with the active physiological growth stage and hence there was an increase in LAI starting from spring (March) and ending in early autumn. The decrease in LAI during autumn is due to the leaf senescence followed by the abscission (Halilou *et al.* 2016). The LAI data from October 2016 onwards is not available because of instrument failure and due to the heavy flood in the forest, the LAI could not be taken in the months of May and June 2016.

3.2 *Turbulence characteristics*

The turbulence characteristics of the site were analysed (table 2a and b) during the whole period and four different seasons as well as day and night in different bin widths of friction velocity (u^*) and standard deviation of vertical velocity (σ_{w}). During the whole period of study, the percentage of occurrence of u^* (52.24%) and σ_{w} (44.32%) was noted in the lower turbulence range corresponding to wind speeds below 0.2 m s^{-1}. Out of the four seasons, the higher occurrence of lower turbulence events (u^* and σ_{w} < 0.2 m s^{-1}) was observed during winter and post-monsoon

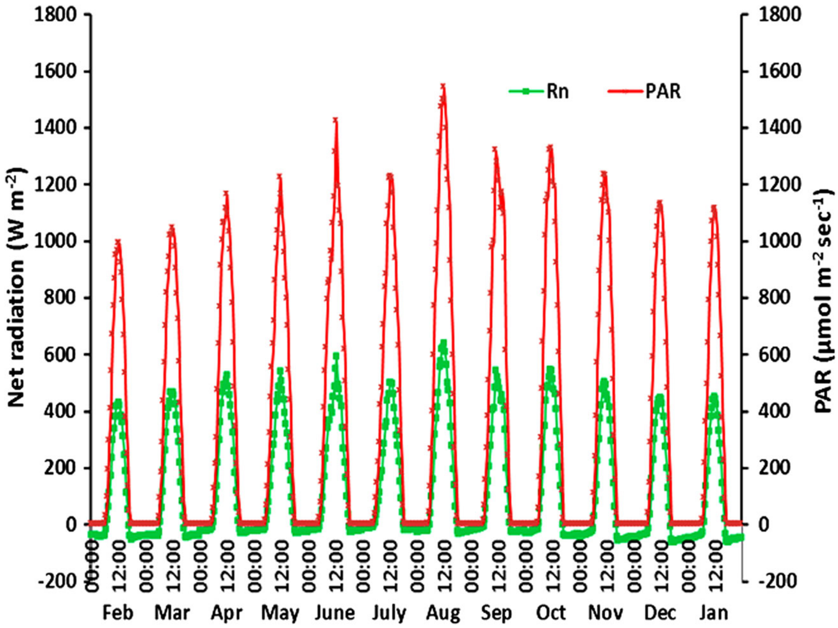

Figure 3. Diurnal variations of net radiation and PAR (monthly mean) from February 2016 to January 2017.

seasons. The occurrence of high-turbulence events in the pre-monsoon season indicated the prevalence of strong winds and surface heating during that season. The analysis of day and night variation of u^* and σ_w indicated the calmness of the atmosphere during winter and post-monsoon nights where u^* and σ_w occurred about 90% in the range of 0–0.2 m s^{-1}.

Atmospheric stability conditions have been divided (table 2c) into five classes during different seasons and day–night, using the stability parameter $(z - d)/L$, where d is the zero plane displacement, L is the Obukhov length and z is the measurement height. In the whole time series, the highest occurrence (29.85%) of $(z - d)/L$ was found to be within a moderately unstable range $(-1 < (z - d)/L < -0.05)$. Despite the seasons, the highest percentage (about 50%) of the moderately unstable range $(-1 < (z - d)/L < -0.05)$ occurred during the daytime.

3.3 *Surface fluxes and energy balance*

The diurnal pattern of net radiation seems to dictate the energy fluxes. More energy was portioned into sensible and latent heat during the midday period. From the month of February 2016 to December 2016, the latent heat fluxes were found to be higher than sensible heat fluxes due to the large evapotranspiration (ET; figure 4), whereas the opposite was observed in the month of January 2017 due to the dry soil conditions as well as the low LAI of the forest canopy. The magnitude of the diurnal peaks of the latent heat fluxes increased continuously from February (161 W m^{-2}) to April (331 W m^{-2}) due to the vegetation growth in the pre-monsoon season as well as due to the wet soil caused by rainfall associated with Nor'westers (Rocha *et al.* 2004). The continuous leaf development process was indicated by the gradual increase in the LAI. In the months of May and June, a decrease in the diurnal peak of the latent heat flux (LE) was observed compared to April in the forest, which may be attributed to less evaporation as a result of less rainfall received by the site compared to April. The lower diurnal peak of LE fluxes in the month of July compared to August is due to the less radiation received in July as a result of cloudy conditions of the sky. The estimated mean annual ET of the forest was 2.8 ± 0.19 mm day^{-1} during the period of study. The diurnal monthly average of ET showed its peak value of 0.58 mm h^{-1} in the month of April 2016.

It is a common practice to assess the quality of eddy fluxes by checking the energy balance closure. The energy balance closure is expressed as:

$$Rn - G = H + LE,$$

where Rn is the net radiation, G is the soil heat flux, H is the sensible heat flux and LE is the latent heat flux.

Table 2. *(a) Occurrence (%) of friction velocity (u*) in different bin limits during the whole period and in different seasons. (b) Occurrence (%) of standard deviations of vertical velocity fluctuations (σ_w) in different bin limits during the whole period and in different seasons. (c) Occurrence of stability parameter ((z − d)/L) in different bin limits during the whole period and in different seasons.*

	Hours	Whole period	Winter	Pre-monsoon	Monsoon	Post-monsoon
(a) u^* limits (m s^{-1})						
0–0.2	a	52.24	65.84	34.57	48.83	65.40
0.2–0.4	a	24.46	17.82	26.53	29.41	21.32
0.4–0.8	a	20.68	15.33	31.03	20.71	13.04
Above 0.8	a	2.61	1.01	7.88	1.04	0.24
0–0.2	d	17.66	22.22	9.46	15.75	27.06
0.2–0.4	d	36.18	36.72	26.45	40.97	40.45
0.4–0.8	d	41.46	39.31	49.03	41.98	32.20
Above 0.8	d	4.69	1.75	15.06	1.30	0.29
0–0.2	n	76.65	92.02	53.95	74.07	93.09
0.2–0.4	n	14.99	5.38	25.92	18.64	5.61
0.4–0.8	n	6.83	1.74	16.36	6.21	1.29
Above 0.8	n	1.52	0.87	3.78	1.08	0
(b) σ_w limits (m s^{-1})						
0–0.2	a	44.32	60.09	26.60	38.48	59.17
0.2–0.4	a	19.21	11.68	21.79	25.10	14.75
0.4–0.8	a	31.83	26.30	38.81	33.89	25.43
Above 0.8	a	4.65	1.92	12.80	2.53	0.65
0–0.2	d	9.49	13.99	4.25	5.56	18.53
0.2–0.4	d	18.00	14.96	12.93	23.67	18.82
0.4–0.8	d	63.96	66.90	59.20	66.67	61.29
Above 0.8	d	8.55	4.15	23.62	4.11	1.36
0–0.2	n	70.64	89.47	44.85	65.79	91.11
0.2–0.4	n	16.48	6.59	26.77	21.35	5.95
0.4–0.8	n	10.41	3.07	21.79	11.04	2.93
Above 0.8	n	2.47	0.87	6.58	1.81	0
(c) $(z - d/L)$ limits						
< -1	a	14.66	22.53	8.29	11.59	20.53
-1 to -0.05	a	29.85	29.76	24.85	32.63	31.51
-0.05 to 0.05	a	10.26	3.90	19.20	10.33	4.75
0.05–1	a	27.25	18.37	34.78	30.88	19.83
> 1	a	17.98	25.43	12.87	14.57	23.37
< -1	d	13.89	20.11	7.70	12.38	17.15
-1 to -0.05	d	54.69	57.61	49.51	56.63	54.31
-0.05 to 0.05	d	14.62	5.80	26.86	15.35	7.63
0.05–1	d	12.82	10.42	14.17	13.45	13.08
> 1	d	3.96	6.06	1.75	2.19	7.83
< -1	n	14.75	24.34	7.38	10.49	21.89
-1 to -0.05	n	11.71	10.71	7.44	14.75	13.58
-0.05 to 0.05	n	5.88	2.91	10.98	5.74	2.19
0.05–1	n	38.98	23.21	53.60	44.08	27.25
> 1	n	28.68	38.82	20.60	24.93	35.09

a: Both daytime and night-time data; d: only daytime data; n: only night-time data.

We have made an attempt to address the energy balance closure of the study area by estimating the balance between half hourly average of available net radiation (Rn) and fluxes of LE, H and G. The energy balance closure obtained is 78% using half hourly data for the whole period of study (figure 5), which is within the acceptable limit (53–99%) as reported from 22 FLUXNET sites (Wilson *et al.*

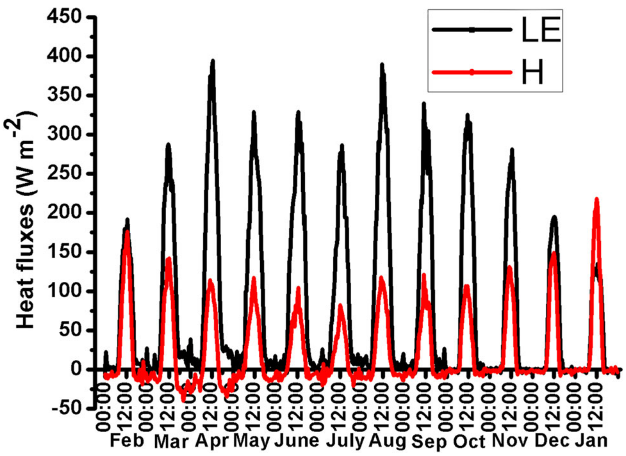

Figure 4. Diurnal variations of latent heat and sensible heat fluxes (monthly mean) from February 2016 to January 2017.

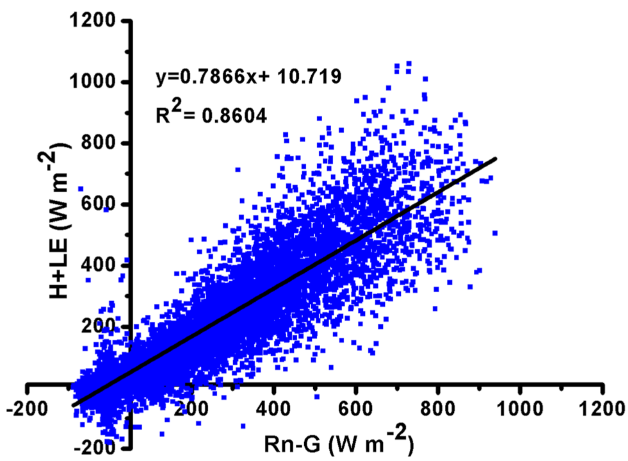

Figure 5. Energy balance closure of the whole study period considering half hourly averaged data.

2002). This type of partitioning is reported to be affected by the type of vegetation, canopy architecture and radiative property (Hurk *et al.* 2001), similar mechanisms might operate in our study resulting in flux deficit.

The poor closure was recorded under the stable conditions, viz., friction velocity <0.2 m s^{-1} and $\sigma_w < 0.4$ m s^{-1}. The closure increased with the increase in atmospheric turbulence and reached up to 90% in the periods with high turbulence (u^* and $\sigma_w > 0.8$ m s^{-1}). Fairly good closure was recorded, about 81%, under moderately unstable conditions ($-1 < (z-d)/L < -0.05$) and 83% under the neutral conditions ($-0.05 < (z-d)/L < 0.05$). It is noted that under very unstable conditions ($(z-d)/L < -1$), closure reduced to 71%.

3.4 *CO_2 fluxes*

In this study, a maximum CO_2 flux of -9.97 µmol $m^{-2} s^{-1}$ (figure 6) was observed above the canopy during summer, in the month of June around noon, which can be attributed to the high PAR for photosynthesis coupled with a higher LAI during that period as leaf area indicates the ability of photosynthate assimilation, stomatal density and amount of incident PAR intercepted by the forest (Bonan 1993; Greco and Baldocchi 1996). A gradual increase in CO_2 uptake from winter (-3.69 µmol $m^{-2} s^{-1}$) in the month of February to summer might be due to the gradual increase in the LAI from February to June. Figure 7 shows a good correlation ($r^2 = 0.74$) between the monthly representative LAI and monthly maximum negative CO_2 flux, only those months when the LAI data are available is considered to establish the relationship. The increase in the LAI might have contributed to the increment of biomass resulting in a C sink by a mechanism reported by Tan *et al.* (2010) in a primary forest. We do not have ample evidence on how much of C was sequestered by the forest ecosystem of our study due to the non-availability of the soil CO_2 efflux data. The percentage of captured C lost by autotrophic respiration is variable among terrestrial ecosystems, as it depends on the main climatic characteristics such as temperature, precipitation and geographical factors such as latitude and altitude (Zhang *et al.* 2009). The results of the peak CO_2 uptake of the study area (≈ -10 µmol $m^{-2} s^{-1}$) is relatively lower compared to the results reported from the other temperate deciduous forests reported by Goulden *et al.* (1996), Greco and Baldocchi (1996) and Saigusa et al. (2002), probably due to the lower LAI of the forest canopy in the present study. The flux of CO_2 at the beginning of spring and at the end of autumn was almost zero which might be due to a small value of the LAI and the results are well corroborated with some other findings (Wilson and Baldocchi 2000). A lower flux of CO_2 was recorded in the KNP ecosystem in the months of January and February in winter due to the less leaf expansion rate. We report here a good correlation of photosynthetic C fixation by the canopy with LAI and are in good agreement with Mori *et al.* (2010), where a relationship of the leaf area with photosynthesis and respiration is addressed in trees.

During the last three monsoon months, July, August and September, less CO_2 flux (-6 to

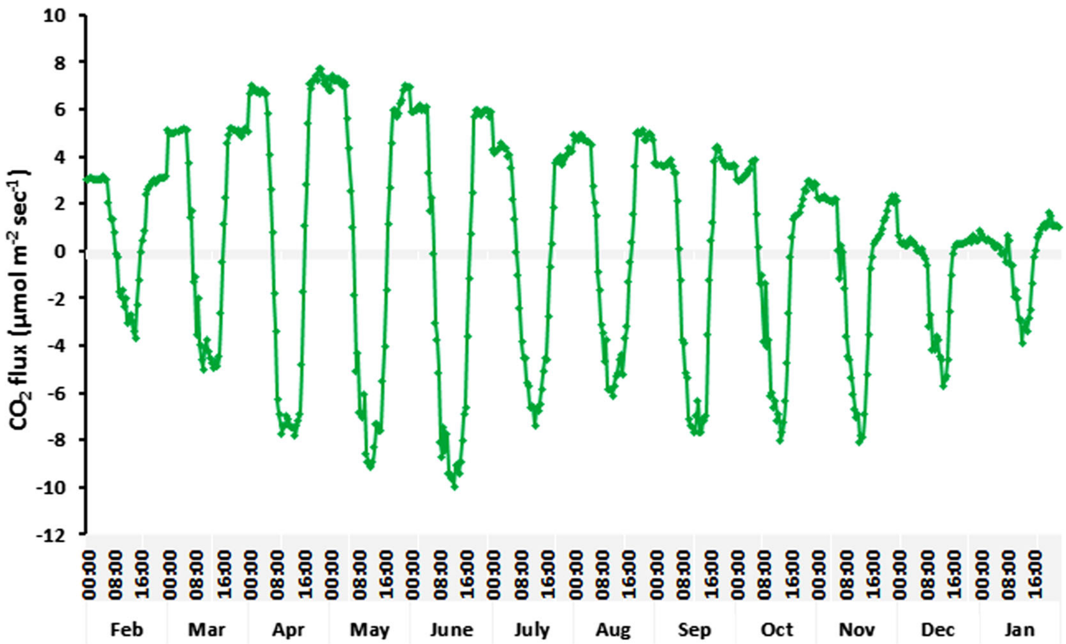

Figure 6. Monthly mean diurnal variations of half hourly CO_2 flux from February 2016 to January 2017.

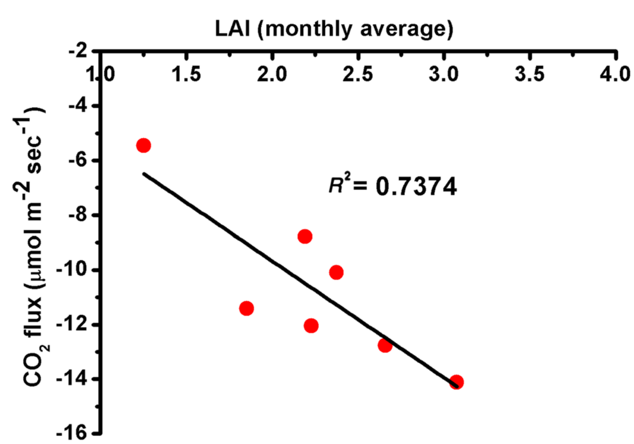

Figure 7. Relationship between monthly averaged LAI and maximum monthly value of negative CO_2 flux during the period of study.

-7 µmol m^{-2} s^{-1}) was measured in the KNP ecosystem, which might have been caused by higher emissions from the soil under the wet conditions (Heinemeyer *et al.* 2007) as a result of high monsoon rainfall. The variations in CO_2 flux could be better assessed with the continuous measurement of soil respiration in our study as CO_2 flux may result from differences in either the assimilation rate or the respiration rate (Wilson *et al.* 2001). The influence of the PAR on CO_2 flux during the different period was investigated and shown in figure 8(a–d). A strong influence of the PAR on CO_2 flux was observed (figure 8b) during the months of May 2016 and June 2016. A high scatter between PAR and CO_2 flux (figure 8c) was observed in the mid-monsoon months (July–August), in these months the CO_2 flux above the canopy was mostly governed by emissions of CO_2 from the wet soil during monsoon. Our results of the least-squares fit between PAR and CO_2 flux presented in figure 8(a, b and d) are in good agreement with the rectangular hyperbolic function reported by Ruimy *et al.* (1995), Rodda *et al.* (2016) and Watham *et al.* (2014).

Vapour pressure deficit (VPD) is an important parameter which regulates the stomatal closure of leaves and thus plays an important role in controlling CO_2 fluxes in the atmosphere. Figure 9 shows a comparison between the diurnal variation of VPD and CO_2 flux. The high LAI of the canopy was recorded during the monsoon season compared to other seasons (Deb Burman *et al.* 2017); hence, the results of the monsoon season are presented here. During the monsoon months, VPD attained the diurnal peak at late afternoon hours which correspond to less negative CO_2 flux above the canopy possibly due to the partial stomatal closure with an increase in VPD after a threshold value. Our results are well corroborated with the findings of Jha *et al.* (2013). A sudden decrease in CO_2 flux in the ecosystem in the month of July may be attributed to the low VPD in July (resulted due to higher rainfall) compared to other monsoon

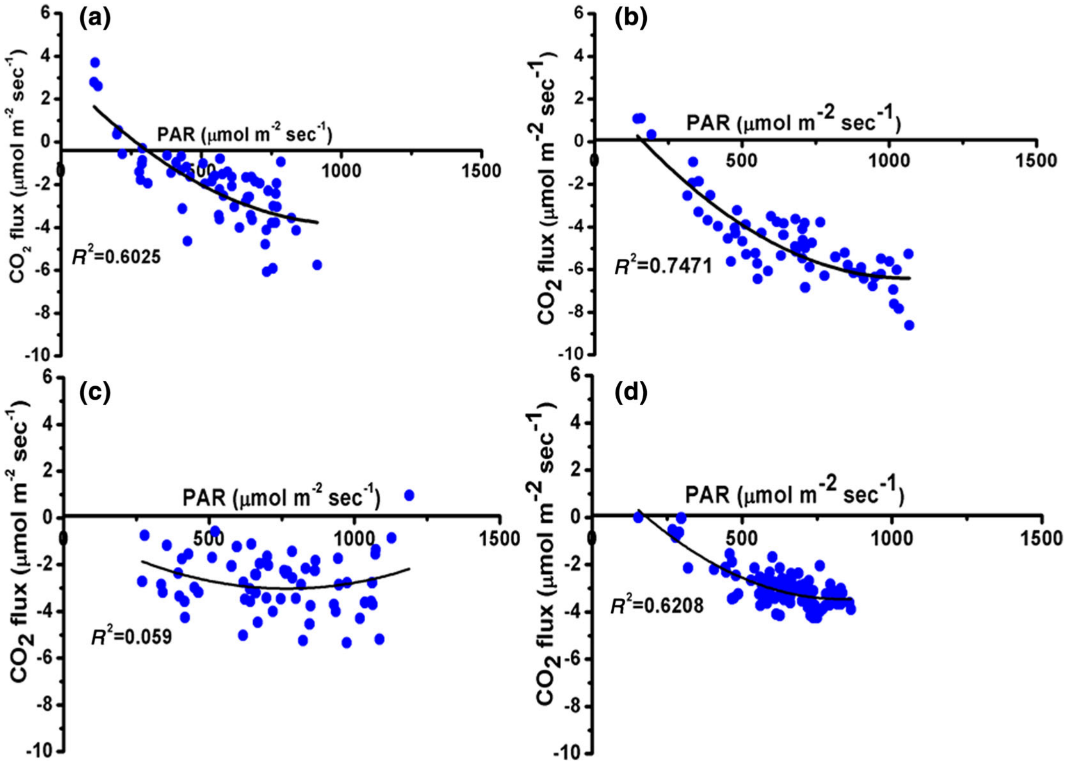

Figure 8. Relationship between daytime average of PAR and CO_2 flux in different months of study: (**a**) March–April 2016; (**b**) May–June 2016; (**c**) July–August 2016; (**d**) September–November 2016.

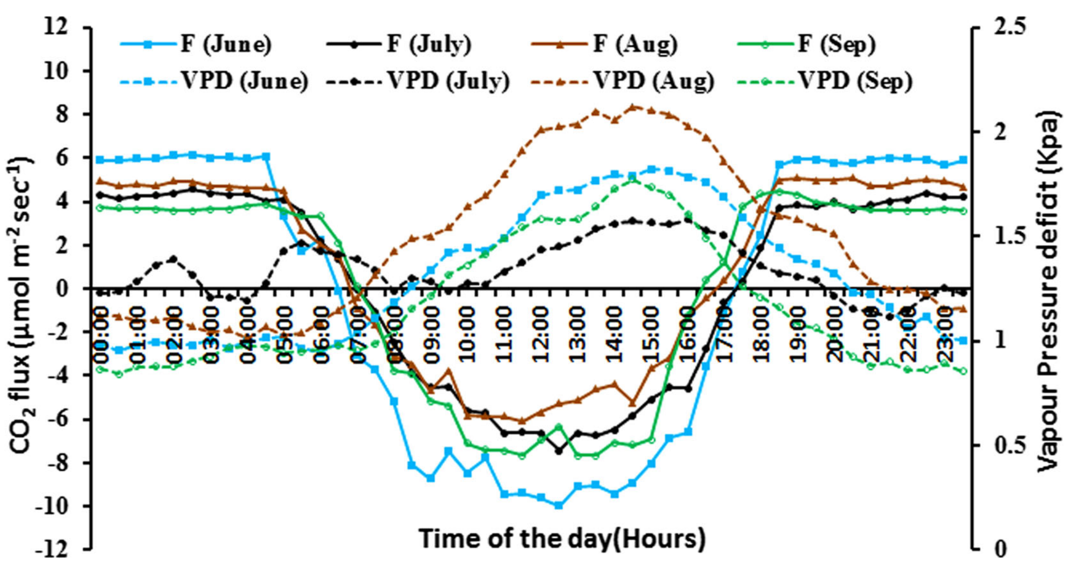

Figure 9. Diurnal variations (monthly mean) of CO_2 flux (indicated by 'F') and VPD from June 2016 to September 2016.

months. The annual NEE of the site calculated from the turbulent CO_2 flux above the canopy is found to be 84.21 g C m^{-2} yr^{-1}. Our results of NEE of the forest are in agreement with the findings of boreal forest (Lindroth *et al.* 1998). Further investigations on net ecosystem productivity and ecosystem respiration of the forest are in progress.

4. Conclusions

The results of monthly and seasonal variations of surface energy and CO_2 fluxes and their relationship with meteorological conditions from an unexplored forest of India are reported here for the first time. The study showed a strong influence of leaf development on the seasonal and monthly behaviour of CO_2 flux. During the period of study, the PAR above the canopy was found to be a key driver which controlled the diurnal pattern of CO_2 fluxes. A better correlation between the PAR above the canopy and CO_2 flux was observed just before the starting of the Indian summer monsoon. The maximum CO_2 flux of -9.97 μmol m^{-2} s^{-1} above the canopy was observed in the month of June. The CO_2 efflux from the soil and VPD of this unexplored forest played an important role in controlling the seasonal behaviour of the CO_2 flux above the canopy during the monsoon season. From the energy flux partitioning analysis dominance of LE over the sensible heat flux was observed during the course of the investigation and the estimated mean annual ET of the forest was 2.8 mm day^{-1}. A fairly good energy balance closure was observed at the site which increased with the increase in atmospheric turbulence. The highest energy balance closure was observed under the neutral conditions.

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