Biosphere Atmosphere Exchange of CO₂, H₂O Vapour and Energy during Spring over a High Altitude Himalayan Forest in Eastern India

Abhijit Chatterjee¹²*, Arindam Roy¹, Supriyo Chakraborty³, Anand K Karipot⁴, Chirantan Sarkar¹, Soumendra Singh⁵, Sanjay K Ghosh²⁵, Amitabha Mitra⁵, Sibaji Raha¹²⁵

¹ Environmental Sciences Section, Bose Institute, Kolkata 700054, India
² National Facility on Astroparticle Physics and Space Science, Bose Institute, Darjeeling 734101, India
³ Center for Climate Change Research, Indian Institute of Tropical Meteorology, Pune 411008, India
⁴ Department of Atmospheric and Space Science, Savitribai Phule Pune University, Pune 411007, India
⁵ Center for Astroparticle Physics and Space Science, Bose Institute, Kolkata 700091, India

ABSTRACT

For the first time, the exchange of greenhouse gases, such as CO₂ and H₂O vapour, between the biosphere and the atmosphere at an eastern Himalayan site in India has been investigated. This study was carried out over a high altitude (2286 m asl) evergreen coniferous forest (27.04°N, 88.08°E), where we measured the fluxes of CO₂ and H₂O vapour along with the sensible and latent energy using the eddy covariance method both above (38 m) and within (8 m) the canopy, the soil-CO₂ flux and the vertical profile of CO₂ during spring (March–April) in 2015. The mean eddy flux of CO₂ above the canopy was –2.8 ± 6.5 µmol m⁻² s⁻¹, whereas it was 0.6 ± 0.4 µmol m⁻² s⁻¹ within the canopy. The mean flux of H₂O vapour above the canopy (1.5 ± 1.8 mmol m⁻² s⁻¹) was three times higher than within the canopy (0.5 ± 0.6 mmol m⁻² s⁻¹). The mean flux of CO₂ emitted from the soil surface was 1.6 ± 0.1 µmol m⁻² s⁻¹. The diurnal variation showed high sequestration of CO₂ during daytime, when the negative flux increased beyond –10 µmol m⁻² s⁻¹. We observed that precipitation significantly enhanced CO₂ sequestration (by approximately fourfold) as well as H₂O vapour emissions (by approximately threefold) by the tall canopies. Overall, during the entire study period, the net ecosystem exchange (NEE) was –656.5 g CO₂ m⁻², suggesting that the evergreen coniferous forest in the eastern Himalaya acts as a net sink of CO₂ during spring. Therefore, we can estimate the sequestration of anthropogenic carbon emission by the eastern Himalayan forest ecosystem, improving the national greenhouse gas inventory.

Keywords: Eddy covariance; Coniferous forest; Greenhouse gases; Himalaya.

INTRODUCTION

The concentrations of global greenhouse gases are increasing due to anthropogenic activities and land use pattern changes (Canadell et al., 2007; Le Quéré et al., 2009). Between the years 1750 and 2011, cumulative anthropogenic CO₂ emissions to the atmosphere were 2040 ± 310 Gt CO₂ (Edenhofer et al., 2014). Atmospheric CO₂ concentration has reached ~405 ppm in 2016 (https://www.co2.earth). Terrestrial forest fixes 30% of these anthropogenic carbons annually (Schulze, 2006; Canadell et al., 2007). A recent study by Ray and Jana (2017) has reported that the Indian Sundarbans sequestered a total of 2.79 Tg C which was nearly 100% of the total carbon emission (2.83 Tg C) from the nearest Kolaghat thermal power plant in West Bengal, India, for the generation of 7.5 × 10⁶ MW of energy during 2010–2011. Thus terrestrial ecosystem provides a way out against the increasing CO₂ and global warming by fixing the anthropogenic inorganic carbon in the atmosphere (Schimel et al., 2001). Various CO₂ capture technologies have attracted the attention of the researchers worldwide. People are utilizing CO₂ directly in various small- and medium-scale industries (soft drinks, foaming, welding, propellants etc.), fixing carbon into microalgae through photosynthesis for the production of biofuel and also indirectly utilizing CO₂ through the conversion to chemicals and energy products (Huang and Tan, 2014). Reduction in fossil fuel activities could effectively reduce CO₂ emission with no doubt but it would also slow down the economical growth (Liou, 2015; Lin, 2015). However, the carbon sequestration through the natural processes (sequestration by ocean, forest etc.) is considered to be the best, effective
and the potential way-out of CO₂ capture which helps to achieve sustainability in energy and environment.

The conversion of inorganic carbon (CO₂) to organic carbon (glucose) through photosynthesis is one of the major processes by which fixation of atmospheric CO₂ takes place. The Gross Primary Production (GPP) by terrestrial plants is calculated to be 123 ± 8 Pg C year⁻¹ (Beer et al., 2010). The Net Ecosystem Exchange (NEE) is the net CO₂ flux from the ecosystem that can be calculated by subtracting GPP and respiration of that ecosystem (Chapin et al., 2006). Terrestrial plants uptake one in eight molecules of atmospheric CO₂ during photosynthesis and respiration of plants and soil organisms return same number of CO₂ in a year. This exchange characterized by large-scale regional variability is the key to estimate whether a terrestrial ecosystem works as a net source or sink of atmospheric CO₂ (Reich, 2010). A recent study in air quality enhancement zones over Taiwan showed that an individual tree could capture as high as 9 metric tons of carbons during its lifetime and improve air quality significantly (Wang et al., 2015).

The eddy covariance system is the most widely used direct method for measurement of fluxes of CO₂, water vapour, and energy between biosphere and atmosphere (Baldocchi, 2003). Number of studies has been done all over the world using eddy covariance technique in different types of terrestrial ecosystems like temperate deciduous forests (Wesely et al., 1983; Verma et al., 1986; Saigusa et al., 2002; Rebmann et al., 2010), boreal forest (Black et al., 2000), Pinus forest (Suni et al., 2003), savanna (Eamus et al., 2001), grassland (Verma et al., 1989), tropical forest (Fan et al., 1990). As far as India is concerned, very few studies were conducted on the measurement of biosphere-atmosphere exchange fluxes of greenhouse gases, such as, at a mixed deciduous forest in central part of India (Jha et al., 2013), over a tropical mangrove ecosystem in Sundarban (Mukhopadhyay et al., 2000; Jha et al., 2014; Rodda et al., 2016) using this method. However, no such study, to the best of our knowledge has been carried out at any high altitude Himalayan forest in India.

The Eastern Himalayan region within its boundary of 524,190 km² includes 3 of the 34 global biodiversity hotspots. Eastern Himalayan sub-alpine coniferous forest is one of the most ecologically concerning terrestrial ecosystems in India. Land-use and land-cover changes contribute to local and regional climate changes (Chase et al., 2000) and global climate warming (Penner et al., 1994; Houghton et al., 1999) which in turn impact on biodiversity (Chaplin et al., 2000; Sala et al., 2000), influencing the reduction in species’ diversity (Franco et al., 2006). These changes also affect the ability of biological systems to support human needs (Vitousek et al., 1997). Shankar Raman reported that the North Eastern states of India lost more than 1000 km² of forest due to human-induced activities between 1989 and 1995 (Raman, 2001). Thus, the studies on greenhouse gas exchange between biosphere and atmosphere over several ecosystems at eastern part of Himalaya are of paramount importance in order to develop the idea about the potential of the ecosystems for greenhouse gas sequestration.

The present study on CO₂, H₂O and energy fluxes between atmosphere and coniferous forest ecosystem has been conducted for the first time over a high altitude environment at eastern Himalaya in India. The present study was focused on understanding 1) the variations in the exchange fluxes of CO₂, H₂O and energy components on diurnal scale, 2) the role of soil in emitting CO₂ into the atmosphere, 3) the effect of rain on the CO₂ sequestration and H₂O vapour emissions and 4) the vertical profile of CO₂ on diurnal scale to understand the biosphere to atmosphere emission/lateral advection of CO₂ and its storage between the near-surface to above the canopy level during spring (March–April) in 2015.

**STUDY SITE AND SYNOPtical METEOROLOGY**

The study site (Fig.1), known as Selimbong forest (27°04'N; 88°08'E; 2286 m amsl) under Dhotrey range of Darjeeling division of Department of Forest, Government of West Bengal, India, consisting of Japanese cedar trees is a part of sub-alpine coniferous forest dominated by large evergreen tree called Cryptomeria japonica mixed with angiosperm vegetation. The height of a mature cedar tree is typically 20–25 meter with a trunk diameter of around 1 m. Introduced around 150 years ago by British planters, C. japonica has become the most successful exotic species in the hills. The other species in the forest are Michelia spp., Castanopsis hystrix, Acer campbellia etc. The forest floor is dominated mostly by angiosperms. Many species of orchids and medicinal plants like Aconitum bisma, Aconitum spicatum, Swertia chirayita, Potentilla fulgens, Taxus wallichiana, Mahonia napaulensis, Polygonum amplexicaulis are very common in this forest. Sandy loam, red and yellow pedozolic soil is the characteristic of this area. Unaltered sedimentary rocks and metamorphic rock are common rock type found in this region. Several perennial hill streams and Lhodoma river catchment surround the forest site. The site is basically free from inhabitants with no anthropogenic and vehicular activities. The nearest road with very low vehicular activities is around 7 km away from the study site. The tower was erected on a flat surface in the study area.

The variations in meteorological parameters during the study period have been shown in Fig. 2. The average temperature was 11.1°C during the study period. The warmest day was found to be 16 April 2015 when average temperature reached ~16°C. On the other hand, coldest day was 5 March 2015 when temperature went down below 6.0°C. Relative humidity varied from as high as 98% to as low as 47% with an average of 81%. Diurnal variation reveals high humidity (> 80%) during nighttime. The average solar radiation was found to be 312.5 W m⁻² with maximum intensity during 13:00–14:00 reaching ~600 W m⁻². Wind speed varied from 0 to 4.5 m s⁻¹ with an average of 1.1 m s⁻¹ during the study period. Maximum wind speed was observed during afternoon hours whereas during night it became calm and stable with very low winds. The total rainfall amount was recorded to be 198.8 mm. Most of the days in March were dry whereas several days with heavy rainfall was recorded in April. Highest rainfall in the study period (~46 mm) was recorded on 12 April 2015. However, the
meteorological data from the nearest observatory (12 km aerial distance) of Bose Institute are recorded on a regular basis. Based on the last ten years (2008–2017) climatology, the temperature during winter (Dec.–Feb.) was found to range between 1.5°C (during 05:00–06:00) and 12°C (at 13:00–14:00). Relative humidity remains around 80% with low wind speed of around 1 m s⁻¹. Snowpack was not observed during winter. The mean temperature remained highest (~21°C) during monsoon (June–Sept.) whereas it remained ~17°C during post-monsoon (Oct.–Nov.).

**METHODS**

**EC Flux Measurement Systems**

The flux tower was equipped with a closed path infrared gas analyzer system (IRGA), LI-7200 (LICOR, Lincoln, NE, USA), in combination with an analyzer interface unit and flow module (LI-7550) to measure the densities of carbon dioxide and water vapour at two heights, 8 and 38 m. A three dimensional (3D) sonic anemometer, Gill WindMaster Pro (Gill Instruments Limited, UK), was installed and co-located with the gas analyzers at 8 and 38 m to measure the orthogonal wind velocity components (along x, y and z axis) and sonic temperature. The measurements from the sonic anemometer and IRGA were recorded at a frequency of 10 Hz.

**Soil-CO₂ Flux Measurement Systems**

Four soil-CO₂ flux chambers (LI-8100A, LI-COR, USA) were installed on the forest floor equidistant from the tower base. The chambers are connected and powered by an analyzer control unit consisting of infrared gas analyzers, data logger and pump (flow rate of 3 L min⁻¹) and a multiplexer (LI-8150). We carried out the vertical profile measurements by drawing ambient air from 1, 5, 8, 11, 20, 25 and 38 m height from the ground.

The analyzers (EC and soil-CO₂ flux) were factory calibrated followed by the installation at the site. Normally, during the factory calibration, two important steps are performed: determining the calibration coefficients and setting zero and span. For zero check, chemical scrubber (soda lime for removing CO₂ and magnesium perchlorate for removing water vapour) is used for making CO₂ and H₂O free air. Usually, the standard CO₂ gas of the concentration in the range 500–1000 ppm is used for CO₂ span. The analyzers were calibrated with the standard CO₂ gas of the concentration of 745 ppm, whereas a dew point generator is used for H₂O vapour span. Dew point temperature is chosen 3–5°C less than the ambient temperature to avoid the condensation problems. Span is a linear function of absorbance and hence there is an offset term and a slope term and both of them are determined at the factory. When a normal span is set by the user, the offset term changes only. The slope term can be changed by performing a secondary span at a much different concentration than the normal span.

**Measurement of Meteorological Parameters**

The meteorological data (temperature, wind, solar radiation, relative humidity, rainfall etc.) were collected from the meteorological tower equipped with a weather station with the sensors like temperature and relative humidity (Model No. HMP45C-L, Campbell Scientific, USA), wind speed and wind direction (Anemometer: Model
No. 05103, Young), total incoming solar radiation (400–1100 nm) (Pyranometer: Model No. SP Lite2, Kipp and Zonen) and rain gauge (TE525 tipping bucket rain gauge). The data was recorded at an interval of 1 min.

**Data Processing and Eddy Flux Calculation**

The data collected from the gas analyzers and sonic anemometers were processed with the EddyPro software (Version 5.0, LI-COR, USA). The fluxes of CO$_2$, H$_2$O and energy were calculated at an interval of 30 min and the total number of samples for each of the CO$_2$, H$_2$O and energy fluxes was 2872.

The fluctuating components like orthogonal wind components $u$, $v$, $w$ and virtual temperature $\theta$ (measured from sonic anemometer), CO$_2$ concentration and water vapour mixing ratio $q$ (measured from infrared gas analyzers) are derived as follows:

$$u = u' - \bar{u}$$  \hspace{1cm} (1)
The components with the prime represent the fluctuations whereas the over-bar represents the half-hour (30 min) average. The fluxes were estimated as the mean covariance between the deviations of the instantaneous vertical wind speed and the parameter under concern.

\[ F_{CO_2} = \bar{w}' \rho CO_2 \]  

\[ H = \rho C_p \bar{w}' \]  

\[ LE = \rho L_{v q}' \bar{w}' \]  

\[ FCO_2, H \text{ and } LE \text{ are the fluxes of CO}_2, \text{ sensible heat and latent energy}; \rho \text{ is the air density}, C_p \text{ is the specific heat at constant pressure and } L_V \text{ is the latent heat of vaporization.} \]

The tilt corrections of sonic measurements were made by axis rotation such that the mean vertical wind speed becomes zero (Wilczak et al., 2001). The data with spikes from electronic and physical noises, though very few, were removed during processing of each data file.

**Soil CO\textsubscript{2} Flux Calculation and Processing**

The gas flux is calculated as the rate at which the gas concentrations are changing inside the chamber. An exponential equation is used for calculation of the flux:

\[ C' = C_s' + [C_0' - C_s']e^{-\alpha t} \]  

\[ C_s', C_0', \text{ and } \alpha \text{ are the empirical parameters estimated from the non-linear curve fit (Eq. (10)). } C_s' \text{ is the CO}_2 \text{ concentration in the soil surface layer under the chamber and fixed over time. } \alpha \text{ is the rate constant. Thus } C', \text{ the concentration of CO}_2, \text{ is the function of time. With the initial slope } (\partial C'/\partial t \text{ at } t = 0) \text{ of the function, the flux is estimated at the time of chamber closing, when } C' \text{ is close to the ambient level (} C_0'). \]

\[ \frac{\partial C'}{\partial t} = \alpha [C_s' - C_0']e^{-\alpha t} \]  

\[ \text{At } t = 0, \frac{\partial C'}{\partial t} = \alpha [C_s' - C_0'] \]

Finally, the flux is calculated from the measured parameters as:

\[ F_C = \frac{VP_0}{RS(T_0 + 273.15)} \frac{\partial C'}{\partial t} \]  

\[ F_C \text{ is the soil CO}_2 \text{ flux, } V \text{ is volume, } P_0 \text{ is the initial pressure, } W_0 \text{ is the initial water vapour concentration, } S \text{ is soil surface area inside the chamber, } T_0 \text{ is initial air temperature, and } \partial C'/\partial t \text{ is the initial rate of change in water vapour dilution-corrected CO}_2 \text{ concentration. The data was processed with SoilFluxPro software of LI-COR, USA. The total number of samples of soil-CO}_2 \text{ fluxes during the entire study period was 1414.} \]

**RESULTS AND DISCUSSION**

**Diurnal Variability in CO\textsubscript{2} and H\textsubscript{2}O Vapour Concentrations**

The springtime concentration of CO\textsubscript{2} above the canopy (38 m) ranged between 389.4 and 397.2 ppmv whereas that within the canopy (8 m) ranged between 390.2 and 398.6 ppmv. The mean CO\textsubscript{2} concentration above the canopy (393.5 ± 1.8 ppmv) was slightly lower (p < 0.05) than that within the canopy (394.2 ± 1.7 ppmv). Figs. 3(A) and 3(B) show the diurnal variations of CO\textsubscript{2} and H\textsubscript{2}O concentrations both within and above the canopy during spring. It shows high CO\textsubscript{2} concentrations during evening to early morning hours (~18:00–06:00) whereas comparatively lower values are observed during morning to afternoon hours (~06:30–17:30). However, minimum values are observed during noon hours at both the heights. The mean CO\textsubscript{2} concentrations during 18:00–06:00, i.e., in absence of the sunlight were found to be higher (p < 0.05) within the canopy (396.4 ppmv) compared to above the canopy (394.8 ppmv) whereas during 06:30–17:30, i.e., in presence of sunlight, concentrations were almost equal (p < 0.05); 392.4 at 38 m and 392.1 at 8 m. Thus, CO\textsubscript{2} concentrations at both the heights were decreased by ~2–4 ppmv during daytime. The uptake of atmospheric CO\textsubscript{2} for photosynthesis by tall canopies and ground level vegetation could result lower daytime CO\textsubscript{2} concentration at both the levels. The atmospheric concentration of CO\textsubscript{2} is controlled by the vertical mixing process (Emeis, 2008). The wind speed was found to be very low during evening till early morning hours over the observation site (as can be seen from Fig. 2(B)) which could favour the accumulation and hence increase the concentration of CO\textsubscript{2} whereas the high wind speed during morning until late afternoon hours could disperse and hence decrease the concentration of CO\textsubscript{2}. During daytime, the higher thermal convection could also dilute CO\textsubscript{2} whereas the high wind speed during daytime until late afternoon hours could disperse and hence decrease the concentration of CO\textsubscript{2}.
and biospheric photosynthesis on the higher nighttime CO₂ concentration compared to daytime over Mahabubnagar, a rural site in India.

The H₂O vapour concentration varied from 8.8 to 16.6 mmol mol⁻¹ within the canopy and from 7.2 to 15.3 mmol mol⁻¹ above the canopy. The mean H₂O vapour concentration within the canopy (13.8 ± 0.8 mmol mol⁻¹) was slightly higher (p < 0.05) than that above the canopy (12.3 ± 0.8 mmol mol⁻¹). The diurnal variations of H₂O vapour concentrations (Fig. 3(B)) within and above the canopy were found to be similar to each other. The concentrations at both the levels were found to increase steadily from ~06:00, i.e., after sunrise and peaked during 13:00–14:00. This could be attributed to the enhanced evaporation from the soil surface and transpiration from plants during daytime.

Diurnal Variability in Eddy and Soil-CO₂ Fluxes

Fig. 4 shows the diurnal variations of CO₂ fluxes above and within the canopy as well as the soil-CO₂ fluxes. The springtime CO₂ flux (FCO₂) above the canopy was found to vary from ~24 µmol m⁻² s⁻¹ to 5.6 µmol m⁻² s⁻¹ whereas that within the canopy varied from ~4.1 µmol m⁻² s⁻¹ to 6.3 µmol m⁻² s⁻¹. The mean FCO₂ above the canopy (~2.8 ± 6.5 µmol m⁻² s⁻¹) was opposite in sign and higher (p < 0.05) than within the canopy (0.6 ± 0.4 µmol m⁻² s⁻¹). CO₂ showed high negative fluxes during daytime and low positive fluxes during nighttime above the canopy. The high negative FCO₂ (atmosphere to biosphere) above the canopy during early noon to early afternoon hours were associated with the uptake of CO₂ by tall canopies for photosynthetic activities under high solar radiative fluxes (Fig. 2(B)). We have also studied the relationship between FCO₂ (NEE) and the total incoming solar radiation (SR) flux to understand the changes in NEE in response to the radiation. As the incoming or downwelling SR fluxes are closely related to the photosynthetic photon flux density (PPFD, which is roughly the double of total incoming SR),

![Fig. 3. Diurnal variations in (A) CO₂ and (B) H₂O vapour concentrations within (8 m) and above (38 m) the canopy.](image-url)
the NEE-SR relationship would help us to better understand the quantum yield (mol CO_2 per mol photons). We have plotted the daily daytime mean NEE and solar radiation for the entire study period where NEE was found to be non-linearly related to SR as, NEE = 9.2 – 3.3 ln (SR + 9.6) with R^2 = 0.4 (see Fig. S1 in supplementary file). This shows significant decrease in NEE with the increase in SR. Above the canopy, the minimum fluxes, i.e., highest negative values were observed during 10:00–13:00 when the mean flux of FCO_2 went below –10 µmol m^{-2} s^{-1} when the solar radiative fluxes were also higher (Fig. 2(B)). However very low positive fluxes during nighttime (atmosphere to biosphere) were observed. For an autotrophic type ecosystem, the nighttime positive fluxes are always lower in magnitude than the daytime negative fluxes (Mildenberger et al., 2009). The mean daytime flux was –6.8 µmol m^{-2} s^{-1} whereas the mean nighttime flux was 1.9 µmol m^{-2} s^{-1} above the canopy. Rodda et al. (2016) reported the peak negative flux of CO_2 of –6.0 µmol m^{-2} s^{-1} associated with the uptake of CO_2 for photosynthesis during summer, 2012 over Sundarban mangrove forest in India. However, they observed minimal variation of nighttime CO_2 fluxes ranging between 4–6 µmol m^{-2} s^{-1} associated with the ecosystem respiration over a one-year study period from April 2012–March 2013. Jha et al. (2013) observed mean flux of CO_2 of –2 µmol m^{-2} s^{-1} in a mixed deciduous forest in Madhya Pradesh in India. The mean CO_2 flux of –3.55 µmol m^{-3} s^{-1} was observed by Patil et al. (2014) in a rural site in India during monsoon (Patil et al., 2014). Rodda et al. (2016) had shown high daytime uptake of CO_2 over three forests in Sundarban, India; –10.2 to –100.2 µmol m^{-2} s^{-1} over Henry Island, –15.7 to –179.3 µmol m^{-2} s^{-1} over Jharkhali and –2.5 to 45.9 µmol m^{-2} s^{-1} over Bonnie Camp during summer, 2011. The maximum uptake of CO_2 above the canopy in this study (–24 µmol m^{-2} s^{-1}) was found to be similar to that observed over a mixed deciduous forest (–25 µmol m^{-2} s^{-1}) as reported by Jha et al. (2013) in central India. Deb Burman et al. (2017) observed GPP of 2110 g CO_2 m^{-2} yr^{-1} with higher values during pre-monsoon and monsoon seasons over a tropical forest ecosystem at Assam in northeast India.

On the other hand, within the canopy, the negative fluxes were observed during 09:30–12:30 and positive fluxes on the rest of the day. The mean flux within the canopy during 09:30–12:30 was –0.9 µmol m^{-2} s^{-1} due to the uptake of CO_2 by small undergrowth vegetation on the ground. The positive fluxes could be associated to the emission of CO_2 from the respiration of ground vegetation and soil (Aubinet et al., 2005) and it was found to be higher during late afternoon to evening hours (greater than 1.5 µmol m^{-2} s^{-1}) compared to night to early morning hours (less than 1 µmol m^{-2} s^{-1}). Baldocchi and Vogel (1996) reported maximum root/soil respiration during midday over a dense coniferous forest because of negligible understory photosynthesis.

The mean soil CO_2 flux as observed from the present study was 1.6 ± 0.1 µmol m^{-2} s^{-1} varying between 1.34 and 1.79 µmol m^{-2} s^{-1}. The diurnal variation shows that the flux started increasing from ~07:00 and peaked during midday, reaching 1.75 µmol m^{-2} s^{-1}. The fluxes remained high (> 1.7 µmol m^{-2} s^{-1}) till 16:00 and then started to fall. Soil-CO_2 flux is resulted from the release of CO_2 produced by autotrophic (plant roots) and heterotrophic (microbes and soil fauna) respiration. Soil-CO_2 flux is strongly correlated with the root biomass (Schlesinger et al., 2000) and contributed by 20% to 90% globally (Boone et al., 1998). Autotrophic respiration from roots and rhizosphere as well as heterotrophic respiration both could play a role in soil-CO_2 flux over our observation site. Autotrophic respiration is very sensitive to the changes in soil temperature whereas...
heterotrophic respiration mainly depends on the ambient temperature (Bauer et al., 2008, Luo and Zhou, 2010). The measurements of soil parameters like soil temperature, soil moisture, soil heat flux etc. were beyond our scope during this study. However, the diurnal variation of soil-CO2 flux was found to be similar to that of ambient temperature and thus it can be said that heterotrophic respiration could be a major factor for soil-CO2 flux. As the temperature and radiative flux increased with the advancement of the day, the decomposition of soil organic matter and biomass could release CO2 and hence enhance flux values.

We know that the net ecosystem exchange (NEE) is the difference between the ecosystem respiration (RE) and gross primary productivity (GPP), i.e., NEE = RE – GPP. During night, NEE can be considered to be equal to RE, as GPP = 0 in the absence of sunlight. Thus the NEE above the canopy and the soil-CO2 flux measured during night would enable us to understand and partition the nighttime respiration between the soil (R\textsubscript{S,N}) and the canopy (R\textsubscript{C,N}). Thus the nighttime NEE at 38 m is equal to the nighttime respiration of the entire biosphere (R\textsubscript{B,N}) and the nighttime soil-CO2 flux is equal to (R\textsubscript{S,N}). The mean of (R\textsubscript{S,N}) and (R\textsubscript{B,N}) were found to be 1.52 μmol m\textsuperscript{-2} s\textsuperscript{-1} and 1.9 μmol m\textsuperscript{-2} s\textsuperscript{-1} respectively. Thus, the nighttime respiration from the soil (R\textsubscript{S,N}) was 0.38 μmol m\textsuperscript{-2} s\textsuperscript{-1} (1.92–1.52) and the soil alone contributed ~80% to the nighttime respiration of the entire biosphere. The net CO2 uptake during the daytime (R\textsubscript{C,N}) was 1.5 μmol m\textsuperscript{-2} s\textsuperscript{-1} when the soil-CO2 flux exceeded 1.7 μmol m\textsuperscript{-2} s\textsuperscript{-1}. This clearly indicates that the positive CO2 flux during the afternoon within the canopy was mostly due to the emission of CO2 from the soil surface and on an average, the soil contribution to the afternoon CO2 flux within the canopy was ~90%.

**Diurnal Variability in H\textsubscript{2}O Vapour, Sensible and Latent Heat Fluxes**

The diurnal variability of H\textsubscript{2}O vapour and latent heat fluxes within and above the canopy is shown in Fig. 5(A). The exchange of water vapour is the result of evaporation from the soil, transpiration of the plants and evaporation of intercepted rain drops and fog (Meiresonne et al., 2003). The atmospheric flux to biosphere intrusion of CO2 and biosphere to atmosphere outflow of water vapour are known to be strongly coupled processes (Mildenberger et al., 2009). The flux of H\textsubscript{2}O vapour above the canopy showed peaks during late morning and afternoon (at around 11:00 and 15:00) hours which could be related to the higher rates of evapotranspiration (with high photosynthetic activity by tall canopies). On the other hand, the flux within the canopy could be due to the evapotranspiration from soil and ground vegetation. The very low FH\textsubscript{2}O is due to very low evapotranspiration during nighttime. The mean daytime flux of FH\textsubscript{2}O above the canopy (1.5 ± 1.8 mmol m\textsuperscript{-2} s\textsuperscript{-1}) was higher than that within the canopy (0.5 ± 0.6 mmol m\textsuperscript{-2} s\textsuperscript{-1}). The mean daytime flux was found to peak at 6.2 mmol m\textsuperscript{-2} s\textsuperscript{-1} above the canopy and 2.6 mmol m\textsuperscript{-2} s\textsuperscript{-1} within the canopy.

Chanda et al. (2013) reported higher daytime water vapour flux (7.8 mmol m\textsuperscript{-2} s\textsuperscript{-1}) than nighttime (3.4 mmol m\textsuperscript{-2} s\textsuperscript{-1}) over three forest sites in Sundarban, India. Rodda et al. (2016) reported minimum water vapour flux of 2.5 mmol m\textsuperscript{-2} s\textsuperscript{-1} in July 2013 and maximum of 5.5 mmol m\textsuperscript{-2} s\textsuperscript{-1} in October 2013 over Sundarban mangrove forest in India. The latent heat flux (LE) varied from –52 to 338 W m\textsuperscript{-2} above the canopy and –27 to 129 W m\textsuperscript{-2} within the canopy. The mean LE above and within the canopy were 68.3 ± 81.5 and 20.6 ± 30.6 W m\textsuperscript{-2} respectively.

The diurnal variability of the sensible heat flux (H) within and above the canopy is shown in Fig. 5(B). It ranged between –30 to 424 W m\textsuperscript{-2} above the canopy whereas that within the canopy varied between –9.8 to 98 W m\textsuperscript{-2}. The mean value of H above the canopy level was much higher (77.7 ± 86.6 W m\textsuperscript{-2}) than that within the canopy (14.3 ± 16.2 W m\textsuperscript{-2}). During the period of 11:00–13:00, H was found to exceed 400 W m\textsuperscript{-2} above the canopy whereas that within the canopy was below 100 W m\textsuperscript{-2}. Thus the partitioning of available energy was slightly more towards sensible heat above the canopy whereas more towards latent heat within the canopy. The Bowen ratio (β) provides information of the partitioning of net radiation into sensible and latent heat and calculated as the ratio of sensible (H) to latent heat (LE) fluxes. Positive values of β were observed during daytime at both the levels. The mean β was higher above the canopy (1.4) than within the canopy (0.7). Kellihier et al. (1997) reported that the mean value of β above the canopy level in Siberia was more than 1.0 during the summer suggesting that more of the available solar energy above the canopy was partitioned to H than to LE over cold regions. This observation has been found to be quite similar to that over eastern Himalayan forest as observed in the present study. The air temperature could also play vital role in governing β as the decrease in temperature limits the evapotranspiration activities (Suzuki et al., 1999). As the present study is mainly conducted in an evergreen forest and only for spring, the effect of the emergence and senescence of leaves of the canopies on the Bowen ratio does not hold any importance. However Wilson et al. (2002) reported that for an evergreen broadleaved forest (as in the case of present study), the β values remains very high (> 1.0) compared to any temperate deciduous forest.

**Effect of Precipitation on Eddy Fluxes of CO2, H2O, H and LE and Soil-CO2 Flux**

In order to investigate the effect of precipitation on the eddy fluxes of CO2, H2O, H and LE, we have compared the diurnal variations between 12 and 13 April 2015 when an intense precipitation of 45 mm occurred during early night (21:00) on 12 April 2015 till early morning (03:00) on 13 April 2015. The other rain events during the study period were not considered for such investigation due to the following reasons. The measurement was started from 1 March 2015 and thus the data was not available before the rain events occurred during 1–3 March 2015. The measurement was stopped after 30 April 2015 (because of various technical issues) and thus data was not available after the events occurred during 21–30 April 2015. Moreover,
Chatterjee et al., Aerosol and Air Quality Research, 18: 2704–2719, 2018

Fig. 5. Diurnal variations in the (A) latent energy and H₂O vapour fluxes and (B) sensible heat fluxes within and above the canopy.

rains occurred during the daytimes in these events. There was thus a single rain event available that started at night on 12 April 2015 and ended in early morning on 13 April 2015 with the clear-sky and sunny conditions before and after rain (daytimes on 12 and 13 April). Hence, this single event was chosen in order to understand the net effect of the precipitation on the daytime photosynthetic activities in terms of CO₂, H₂O, H and LE fluxes.

The eddy fluxes of CO₂, H₂O, H and LE above the canopy are shown in Figs. 6(A)–6(D) whereas the eddy fluxes of CO₂ within the canopy along with the soil-CO₂ fluxes before and after rain are shown in Fig. 7. We observed that the fluxes above the canopy were increased after the rain event. The mean CO₂ fluxes during the period of 11:00–13:00 became more negative and increased ~4 times after the precipitation (from 9.7 µmol m⁻² s⁻¹ to 37.8 µmol m⁻² s⁻¹). The mean H₂O vapour flux during peak period was increased from 1.9 before the rain event to 4.6 mmol m⁻² s⁻¹ after the rain event. The larger negative FCO₂ and positive FH₂O after precipitation indicate that the eastern Himalayan coniferous forest could consume higher amount of CO₂ under the wet condition and efficiently take part in photosynthetic activity compared to the drier condition. Similarly H and LE during the period were also found to be increased by 182 and 117 W m⁻² respectively. Specifically, the increase in LE brings our attention to an important fact. One of our earlier studies over this part of Himalaya observed high loading (~2000 cm⁻³) of cloud condensation nuclei (CCN) during spring (Roy et al., 2017). Thus the high biospheric emissions of H₂O vapour after the precipitation (as observed from the present study) could thus favour the low-level cloud formation in presence of high loading of CCN. A recent study (Wright et al., 2017) has shown that the evapotranspiration of the plants is the major source of the moisture and activates the shallow convection through shallow convection moisture pump (SCMP) mechanism over Amazon during the dry-to-wet transition period. They have shown that SCMP pre-conditions the atmosphere for increasing the rain-bearing convection and aerosols play important roles in modifying such convection. However,
the above mentioned possibilities could not be ruled out over this part of Himalaya but need to be investigated with large number of datasets whether and to what extent precipitation increases evapotranspiration and favours the formation of low-level cloud with the high loading of aerosols acting as CCN.

The diurnal variations of the CO₂ fluxes within the canopy before and after the precipitation are shown in Fig. 7(A). It is observed that the photosynthetic activities (negative NEE) within the canopy did not increase due to the precipitation. But the daytime respiration (positive NEE) within the canopy showed noticeable increase during the afternoon. The afternoon fluxes of CO₂ before the precipitation were less than 1.5 µmol m⁻² s⁻¹ and increased to greater than 2 µmol m⁻² s⁻¹ after the precipitation. This can be explained by the changes in the soil-CO₂ fluxes due to the precipitation.

The diurnal variations of soil-CO₂ fluxes before and after rain event (Fig. 7(B)) show ~30% increase in the mean daytime soil-CO₂ flux (1.4 µmol m⁻² s⁻¹ to 1.8 µmol m⁻² s⁻¹) after the precipitation. The midday (12:00–14:00) flux which was around 1.5 µmol m⁻² s⁻¹ before the rain, reached 2.0 µmol m⁻² s⁻¹ after the rain event. We also observed that the mean daytime ambient temperature before the rain event (12.3°C) was slightly higher than that after the rain event (11.4°C). Even the midday temperature was found to be slightly higher (13.2°C) before the rain compared to after the rain event (12.6°C). Thus we observed that the soil-CO₂ flux was increased in spite of the decrease (statistical significance test could not be performed because of only one rain event) in ambient temperature after the precipitation. Hence the ambient temperature could not be considered as the responsible factor for the high increase in soil-CO₂ flux but the precipitation probably increased the soil water availability/moisture content which in turn could increase the microbial activities and soil-CO₂ flux.

**Fig. 6.** Variations in the eddy fluxes of (A) CO₂, (B) H₂O vapour, (C) sensible heat, and (D) latent heat fluxes above the canopy before (12 April 2015) and after (13 April 2015) the rain event.
We discussed earlier that the increase in soil-CO₂ fluxes affected and changed the sign of FCO₂ within the canopy (from negative to positive) during afternoon (Fig. 4). A close look at the Fig. 4 shows that the NEE values within the canopy changed from negative to positive at 13:00 when the soil-CO₂ flux reached around 1.7 µmol m⁻² s⁻¹. Similarly, Fig. 7(A) shows that the CO₂ flux within the canopy (after the precipitation) changed its sign from negative to positive during 10:30–11:00 when the soil-CO₂ flux reached and remained within 1.7–1.75 µmol m⁻² s⁻¹ during 10:00–11:00. Also the afternoon CO₂ fluxes within the canopy exceeded 2 µmol m⁻² s⁻¹ when the soil-CO₂ fluxes too exceeded 2 µmol m⁻² s⁻¹ after the precipitation. Thus the CO₂ emission within the canopy was not directly affected by the precipitation but it was the increased soil-CO₂ emission due to the precipitation, which enhanced the CO₂ emission within the canopy. This further supports the fact that the CO₂ uptake within the canopy was due to the photosynthetic activities by the undergrowth vegetation whereas the CO₂ emission was mostly contributed by the soil surface.

We observed very low values of Bowen ratio, β (less than 0.5), after the rain events with sunny conditions on some of the rainy days during the study period. This indicates that most of the available energy was used for the evapotranspiration from the wet canopies and the wet soil surface.

We studied another rain event during 30 March–4 April 2015 and that occurred during the daytime and the three consecutive days after this event remained cloudy. We compared the relationship between NEE and SR (as discussed earlier) after this event with normal (without precipitation) cloudy days (see Fig. S2 in supplementary file). This would enable us to minimize the effect of cloudiness on NEE and to get the idea of the net effect of precipitation only. We observed that the slope of the non-linear relationship between NEE and SR during after-rain-cloudy-days was higher than the normal cloudy days suggesting and further supporting the fact that eastern Himalayan conifer forest sequester more CO₂ after precipitation or under wet conditions.

However, such changes in H₂O, H and LE fluxes were not observed within the canopy due to the precipitation.

**Vertical Profile of CO₂**

While the CO₂ near the ground and within the canopy is associated with the emissions from the soil, plant roots and undergrowth vegetation etc., the CO₂ above the canopy is not only associated with the respiration of the tall canopies but also with the lateral advection of CO₂ as well as transported from the long-distant source regions. Our earlier studies (Sarkar et al., 2015; Sarkar et al., 2017; Roy et al., 2017) reported the transport of anthropogenic volatile, semi-volatile and particulate carbonaceous compounds (with the sources similar to CO₂) over an eastern Himalayan high altitude station, Darjeeling (12 km from the present study site) mostly from the polluted western and central parts of the Indo-Gangetic Plain regions during pre-monsoon (March–May). The lateral advection of anthropogenic CO₂ emitted from the fossil fuel and biomass burning from the popular tourist station Darjeeling (March–April being the peak tourist season), the transport of CO₂ from the lowland townships through the valley wind etc. could also contribute to the total CO₂ loading above the canopy. The vertical profile of CO₂ was thus studied in order to understand the effect of the biospheric emissions/sinks of CO₂ as well as the atmospheric input to the biosphere on the CO₂ dynamics from near the ground to above the canopy level.
The vertical profile of CO₂ concentration (expressed as the partial pressure of CO₂, pCO₂) is shown in Fig. 8 for midnight (00:00), morning (07:00), midday (12:00) and evening (19:00). It was measured at the heights of 1 m, 5 m, 8 m, 11 m, 20 m, 25 m and 38 m from the ground. The salient features from the vertical distribution of CO₂ as observed from the figure are as follows:

During midnight (00:00), the pCO₂ near the ground was maximum (~398 ppm) and above this level it showed very low vertical gradient. Most of CO₂ emitted from the respiration of plants and soil is trapped and accumulated near the ground because of calm and stable atmospheric conditions. This could be supported by the very low nighttime friction velocity \( u \times (0.12 \pm 0.03 \text{ m s}^{-1}) \) compared to daytime \( (0.31 \pm 0.06 \text{ m s}^{-1}) \) within the canopy. Hence absence of vertical mixing and atmospheric instability increased pCO₂ near the ground. The time of sunrise during summer in the study site was between 05:30–06:00 and hence 07:00 have been chosen, i.e., after ~1 hour of the sunrise in order to get the idea of the effect of sunrise on the vertical pCO₂ profile. During morning (07:00), i.e., after the sunrise, pCO₂ was found to be reduced by ~1.5 ppm (it achieved a value of 396.5 ppm at 1 m) near the ground. After the sunrise, when surface starts getting heated and vertical mixing starts, nocturnally trapped nighttime CO₂ upwelling and hence near-ground pCO₂ starts decreasing. However, reaching at 20 and 25 m, a little drop in pCO₂ was observed which could due to the uptake or reabsorbing of nighttime trapped CO₂ by tall canopies for photosynthesis under availability of sunlight. During noon (12:00), pCO₂ was found to decrease ~0.8 ppm near the ground from morning hours (pCO₂ at 1 m = 395.7 ppm). As stated earlier that the soil-CO₂ flux during noon hours was highest which could somewhat compensate CO₂ loss near the ground because of vertical mixing and atmospheric instability during noon hours. The upwelling of soil emitted CO₂ could also slightly enhance pCO₂ at 5, 8 and 11 m. However, sharp drops in pCO₂ were found (~5 ppm) at 20 and 25 m which could be associated with the uptake of CO₂ by tall canopies for photosynthetic activities under high solar radiative fluxes during noon hours. However, pCO₂ at 38 m was again found to increase after mixing with free ambient level. The time of sunset during spring in the study site was between 17:30–18:00 and hence 19:00 have been chosen, i.e., after ~1 hour of sunset in order to get the idea of the effect of sunset on the vertical pCO₂ profile. During evening (19:00), pCO₂ did not show any vertical gradient (< 0.4 ppm) from 11 m to 38 m. However, near ground pCO₂ was found to increase by ~2 ppm compared to upper levels. CO₂ after the sunset descends with the stability of the atmosphere. Also, CO₂ emitted from the ecosystem respiration starts accumulated and trapped near the ground as vertical mixing weakens. The eddy covariance method and the vertical profiling method both showed good agreement in respective measurements of CO₂ concentration, for example, CO₂ did not show any vertical gradient (CO₂ at 8 and 38 m were almost equal) during 07:00 as shown in Figs. 4 and 8.

**Comparisons of Net Ecosystem Exchange of CO₂ over Eastern Himalaya with Other Ecosystems**

We have compared the daily mean NEE of CO₂ (–10.6 g CO₂ m⁻² day⁻¹) observed in this study over eastern Himalaya with other studies over India and across the globe. We have considered summer or spring season only to compare with other studies. The daily mean NEE in this study is found to be much higher compared to other forest sites across the globe like grassland site in California, USA (–5.5 g CO₂ m⁻² day⁻¹) (Xu and Baldocchi, 2004), larch
forest in Japan (–0.4 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1}) (Hirano et al., 2003), permafrost ecosystem in Svalbard archipelago (–0.74 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1}) (Lüers et al., 2014) and boreal forest site at Mangolia (–6 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1}) (Li et al., 2005). In a high elevation Glacier Lakes Ecosystem Experiments Site (3190 m asl) in Wyoming, USA, forest before the beetles attacked the trees, the average CO\textsubscript{2} flux was observed to be –1.7 to –2.5 µmol m\textsuperscript{-2} s\textsuperscript{-1}, which is very much comparable to our study site (Frank et al., 2014). Schmid et al. (2000) observed that the mixed hardwood forest in USA acts as a net source of CO\textsubscript{2} with NEE of 0.56 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1} during March–May. Rodda et al. (2016) have reported very low value of NEE (–1.85 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1}) over Sundarban mangrove forest region during Jan.–Mar. 2013. Comparable NEE (9.6 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1}) were observed in mixed deciduous forest site over Nainital, a high altitude forest site at the foothills of Kumaon Himalayas during the Apr.–May in 2013 (Watham et al., 2014). Jha et al. (2013) have reported a mean NEE of –7.7 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1} at a mixed deciduous forest in Madhya Pradesh, India. A recent study by Sarma et al. (2018) has reported maximum NEE of –10 µmol m\textsuperscript{-2} s\textsuperscript{-1} CO\textsubscript{2} over a semi-evergreen forest in Assam, India, during summer (June) which is comparable with the present study. But they reported much larger positive NEE during nighttime compared to the present study suggesting eastern Himalayan high altitude coniferous forest can act as a better sink compared to semi-evergreen forest in Assam during summer.

**Implications of the Results**

The total area of eastern Himalayan coniferous and broadleaf forest is around 170,000 km\textsuperscript{2} (World Wildlife Fund website, http://wwf.panda.org) and its geographical range includes countries like Bhutan, China, India, Myanmar and Nepal. The area of this eco-region is beyond comparison with other national forests like Sundarban (1396 km\textsuperscript{2}) or mixed deciduous forest in Madhya Pradesh (4056 km\textsuperscript{2}) in India. We would like to mention here that the area of this eco-region is comparable with Western-Ghats biodiversity hotspot region (160,000 km\textsuperscript{2}), western Himalayan temperate forests (95,500 km\textsuperscript{2}), Russian far east temperate forests (210,000 km\textsuperscript{2}), Pacific temperate rainforests (295,000 km\textsuperscript{2}), Madagascar forests and shrublands (313,000 km\textsuperscript{2}) and Sierra Nevada coniferous forests (53,000 km\textsuperscript{2}). Thus the eastern Himalayan coniferous and broadleaf forest region could be considered (qualitatively) as a good sink zone of CO\textsubscript{2} during spring (based on our NEE determination of –10.8 g CO\textsubscript{2} m\textsuperscript{-2} day\textsuperscript{-1} during spring). Also, the total carbon sequestration by the entire eastern Himalayan forest region would definitely contribute to the global/regional CO\textsubscript{2} budget to a large extent. We have also observed that precipitation enhances the carbon sequestration to a large extent by this forest and thus the importance of the results of this study increases manyfold as the forest site receives huge amount of rainfall (more than 2500 mm in a year).

The eastern Himalayan eco-region falls into vulnerable category. Apart from species richness and geographical point of view, this study will also establish this ecosystem as a major sink of carbon over Indian subcontinent. The result from this study showing large sink of CO\textsubscript{2}, holds one of the major motivations for the conservation and restoration of this ecosystem.

**CONCLUSION**

A short-term (March–April 2015) study was conducted on the biosphere-atmosphere exchange of CO\textsubscript{2}, H\textsubscript{2}O and energy using the eddy covariance method over a high altitude coniferous forest in the eastern Himalaya in India. The major findings of the study are as follows:

1) Both the CO\textsubscript{2} and H\textsubscript{2}O vapour concentrations within the canopy were slightly higher than those above the canopy.

2) The mean CO\textsubscript{2} flux above the canopy (–2.8 ± 6.5 µmol m\textsuperscript{-2} s\textsuperscript{-1}) was opposite in sign and higher than within the canopy (0.6 ± 0.4 µmol m\textsuperscript{-2} s\textsuperscript{-1}).

3) The mean CO\textsubscript{2} flux emitted from the soil was 1.6 ± 0.1 µmol m\textsuperscript{-2} s\textsuperscript{-1}. Within the canopy, the CO\textsubscript{2} flux was positive only during the afternoon, and the flux increased with the soil-CO\textsubscript{2} flux. This clearly indicates that while the atmosphere to biosphere sequestration of CO\textsubscript{2} above the canopy was due to the photosynthetic activities of tall canopies, the biosphere to atmosphere emission of CO\textsubscript{2} within the canopy was mostly due to CO\textsubscript{2} emissions from the soil.

4) The mean water vapour flux above the canopy was threefold higher than within the canopy. H\textsubscript{2}O vapour emissions from the biosphere to the atmosphere were due to the high evaportranspiration of tall canopies as well as undergrowth surface vegetation and soil.

5) A rain event (with intense precipitation accumulating 45 mm) was examined during the study period, during which we observed that CO\textsubscript{2} sequestration by the tall canopies as well as CO\textsubscript{2} emission from the soil increased after the precipitation. It was also noted that the tall canopies emitted more water vapour to the atmosphere following the precipitation.

6) A prominent vertical gradient (1–38 m) of CO\textsubscript{2}, with a sharp drop in the CO\textsubscript{2} concentration at 20 and 25 m due to the high CO\textsubscript{2} uptake at the top of the canopy, was observed during the noon hour, whereas no such gradient was observed at other times of the day.

7) Overall, we observed that the high altitude Himalayan coniferous forest in eastern India acts as a net sink of CO\textsubscript{2}, with a net ecosystem exchange of –656.5 g of CO\textsubscript{2} m\textsuperscript{-2} during the spring season.

**ACKNOWLEDGEMENTS**

We thank Ministry of Earth Sciences (MoES), Govt. of India, for funding the project. We also thank the Director, IITM for his support and encouragement. We would also like to thank Department of Forest, Govt. of West Bengal, for providing the forest land and permitting us to carry out the observations. We thank Sabayasachi Majee, Technical Assistant of Bose Institute, for technical help and for the active participation in the field work. We would also like to thank Deokumar Roy, Bose Institute, for providing the
logistical support. This study is dedicated to the centenary celebration of Bose Institute.

**SUPPLEMENTARY MATERIAL**

Supplementary data associated with this article can be found in the online version at http://www.aqr.org.

**REFERENCES**


Sarma, D., Baruah, K.K., Baruah, R., Gogoi, N., Bora, A.,


*Received for review, December 30, 2017*

*Revised, April 26, 2018*

*Accepted, April 28, 2018*