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Spatial variability of atmosphere-biosphere CO_2 and H_2O exchange in selected sites of Indian Sundarbans during summer

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Abstract: Spatial variability of atmosphere-biosphere CO_2 exchange was evaluated in Jharkhali, Bonnie Camp and Henry Island – situated, respectively, in the inner, middle and outer estuarine part of Indian Sundarban mangrove ecosystem – using micrometeorological methods, between 15th April and 15th May, 2011. Henry Island and Jharkhali acted as a sink for CO_2 with a rate of 18.94 g m^{-2} d^{-1} and 51.06 g m^{-2} d^{-1}, respectively, whereas the sink strength of Bonnie camp was 1.51 g m^{-2} d^{-1}. A positive correlation was obtained between solar radiation and 'atmosphere to biosphere' CO_2 flux. Varying magnitudes in leaf chlorophyll may be another decisive factor controlling CO_2 exchange. Greater chlorophyll content of the dominant species of a site leads to higher photosynthetic rate and hence increases the magnitude of 'atmosphere to biosphere' CO_2 influx. A mean daytime water vapor flux of 7.83 ± 4.95 m mol m^{-2} s^{-1} and a nighttime of 3.38 ± 3.32 m mol m^{-2} s^{-1} was observed at the three sites. The observed Bowen ratio values reflected a dominance of latent heat flux, compared to that of sensible heat flux in this ecosystem. The ecosystem on the whole acted as a sink for CO_2 (23.83 g m^{-2} d^{-1}) but the magnitude of CO_2 influx was found to vary spatially.

Resumen: La variabilidad espacial del intercambio atmósfera-biósfera de CO_2 fue evaluada en Jharkhali, Bonnie Camp y Henry Island – ubicados, respectivamente, en la parte interna, intermedia y externa de la porción estuarina del ecosistema de manglar de los Sundarbans – usando métodos micrometeorológicos, entre el 15 de abril y el 15 de mayo de 2011. Henry Island y Jharkhali funcionaron como un resumidero de CO_2, con tasas de 18.94 g m^{-2} d^{-1} y 51.06 g m^{-2} d^{-1}, respectivamente, mientras que la fuerza como resumidero de Bonnie Camp fue de 1.51 g m^{-2} d^{-1}. Se obtuvo una correlación positiva entre la radiación solar y el flujo de CO_2 'atmósfera a biósfera'. La variación en la cantidad de clorofila foliar puede constituir otro factor decisivo en el control del intercambio de CO_2. Un mayor contenido de clorofila de las especies dominantes de un sitio resulta en una mayor tasa fotosintética y por lo tanto incrementa la magnitud del flujo de CO_2 'atmósfera a biósfera'. En los tres sitios se observó un flujo promedio diurno de vapor de agua de 7.83 ± 4.95 m mol m^{-2} s^{-1} y uno nocturno de 3.38 ± 3.32 m mol m^{-2} s^{-1}. Los valores observados del cociente de Bowen reflejaron una dominancia del flujo de calor latente en comparación con el flujo de calor sensible en este sistema. El ecosistema como un todo funcionó como un resumidero de CO_2 (23.83 g m^{-2} d^{-1}), pero la magnitud del flujo de entrada de CO_2 varió espacialmente.

Resumo: A variabilidade espacial da troca de CO_2 na atmosfera-biosfera foi avaliada entre 15 de abril e 15 de Maio de 2011 em Jharkhali, Camp Bonnie e Ilha Henry - situados, respectivamente, na parte interior, central e externa do estuário do ecossistema de mangal do

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Sundarban indiano – utilizando métodos micrometeorológicos. A Ilha Henry e Jharkhali comportaram-se como sumidouros de CO_2 com uma taxa de 18,94 g m^{-2} d^{-1} e 51,06 g m^{-2} d^{-1}, respectivamente, enquanto que a capacidade de fixação no Camp Bonnie foi de 1,51 g m^{-2} d^{-1}. Verificou-se uma correlação positiva entre a radiação solar e o fluxo de CO_2 'atmosfera para a biosfera'. As variações de magnitude nas concentrações de clorofila das folhas podem ser outro fator decisivo no controlo da troca de CO_2. Maior teor em clorofila das espécies dominantes de um site leva a uma maior taxa fotossintética e, consequentemente, do aumento do influxo de CO_2 da 'atmosfera para a biosfera'. Uma média diurna do fluxo de vapor de água de 7,83 ± 4,95 m mol m^{-2} s^{-1} e de 3,38 ± 3,32 m mol m^{-2} s^{-1} por noite foi observada nos três locais. Os valores observados do ratio de Bowen refletiram a dominância do fluxo de calor latente, comparada com a do fluxo de calor sensível neste sistema. O ecossistema como um todo agiu como um sumidouro de CO_2 (23,83 g m^{-2} d^{-1}), mas a magnitude encontrada do influxo de CO_2 foi espacialmente variada.

Key words: Bowen ratio, carbon dioxide flux, diurnal variation, mangrove forest, spatial variation, Sundarban, vertical CO_2 profile, water vapor flux.

Introduction

Terrestrial gross primary production (GPP) is the largest global CO_2 flux (~123 ± 8 Pg C $year^{-1}$) driving several ecosystem functions (Beer *et al.* 2010). Denning *et al.* (1995) suggested that the carbon sinks in the northern hemisphere must be larger than previously shown. Global carbon budgets indicate that a large quantity of CO_2 is absorbed by terrestrial ecosystems (Tans *et al.* 1990). Each year, photosynthesizing land plants fix one in eight molecules of atmospheric CO_2, whereas respiration by plants and soil organisms returns a similar number, which is why, the key to accurately predict future levels of atmospheric CO_2 is in understanding how land and atmosphere exchange CO_2 (Reich 2010). The Kyoto Protocol came into existence in December 1997 out of a global concern for increasing CO_2 concentration in the atmosphere, mainly from the ever-increasing usage of fossil fuels. According to this protocol, countries can reduce emissions either by limiting fossil fuel consumption or by increasing net carbon sequestration in terrestrial carbon sinks (Pilegaard *et al.* 2001).

Efforts have been made to understand the exchange dynamics of CO_2 over tropical terrestrial forests, but comparatively less attention is paid to mangrove forests at the land ocean boundary (Schimel 1995). Mangroves are among the most productive coastal intertidal ecosystems in the world, confined to the tropics and subtropics that dominate approximately 75 % of the world's coastline between 25º N and 25º S. They are estimated to cover about 0.17 - 0.20 × 10^6 km^2 (Borges *et al.* 2003). The mangrove ecosystem as a whole is generally net autotrophic, but the water column and the sediments are largely net heterotrophic (Borges *et al.* 2003).

Micrometeorological techniques make continuous monitoring and frequent collection of data possible without disturbing the environment around the plant canopy (Baldocchi *et al.* 1988). Even when these techniques are employed it may be difficult to conclude whether a forest is a net source or a sink for CO_2. The few short and long-term studies conducted in the Indian Sundarbans have produced mixed results. In a short-term study carried out in Jambu Island, Mukhopadhyay *et al.* (2000) concluded that this ecosystem was a sink for CO_2 in the pre-monsoon season, at a rate of 24 × 10^9 kg C $year^{-1}$. By contrast, a study at Lothian Island (Mukhopadhyay *et al.* 2001) found that the ecosystem was a source, with a rate of 1.51 × 10^6 mg day^{-1}. Long-term annual studies conducted at Lothian Island reflected a source character for CO_2 as reported by Mukhopadhyay *et al.* (2002), while in a study at Lothian Island and Sajnekhali in the Indian Sundarbans Ganguly *et al.* (2008) observed a mean net flux of -48.3 g m^{-2} day^{-1} and total sink strength of 206 Gg day^{-1} for the reserve forest area (4264 km^2). These studies show that the nature and the bio-physical behavior of this ecosystem are very difficult to establish with respect to CO_2 flux. The temporal and spatial heterogeneity of the domain makes the study much more complex, requiring the acquisition and analysis of data over decades to study the contributions of such ecosystem to CO_2 flux.

Amongst the biological variables, age of the forest is one of the vital factors that affect CO_2 flux. It is believed that assimilation of carbon is equally balanced by respiration as a forest stand reaches an 'advanced' stage of development (Melillo *et al.* 1996). This hypothetical viewpoint is based on the observed steady decline in net primary productivity with stand age (Gower *et al.* 1996; Ryan *et al.* 1997; Yoder *et al.* 1994). However, most of these studies were carried on managed, even-aged or single species forests. In case of mixed vegetative cover or natural forests with a wide range of age classes and diverse canopy structure such hypothesis cannot be successfully implemented. For example, a 250 year old beech forest (Knohl *et al.* 2003), a 300 year old Nothofagus site in New Zealand (Hollinger *et al.* 1994) and a 450 year old Douglas fir site in Washington (Falk *et al.* 2002) have been found to show net CO_2 sink with strength of varying magnitude.

In the present study the magnitude of daytime CO_2 influx and nighttime ecosystem respiration were investigated using an NDIR gas analyzer at three new sites with heterogeneous vegetation cover, located at the inner, middle and outer estuarine part, in the Indian Sundarbans. The study was conducted at three sites within four weeks, between 15th April and 15th May, to understand the nature of diurnal and spatial variation of CO_2 flux under similar climatic conditions. The vertical stratification of atmospheric CO_2 at five different layers (including below canopy) and their variation with varying micrometeorological parameters were also analyzed.

Materials and methods

Site description

The mangrove forest of the Indian Sundarban lies between 21° 32′ and 22° 40′ N latitude and between 88° 05′ and 89° E longitude and comprises an area of 9630 km^2, out of which 4264 km^2 is under the arena of reserve forest. It extends in the Bay of Bengal towards the south and stretches up to the Dampier-Hodges line in the north. It is the largest delta on the globe, situated in the estuarine phase of the river Ganges and having a unique bioclimatic zone in the land-ocean boundary of the Bay of Bengal. The climate in this part of the continent is grossly demarcated as monsoon (June-September), post-monsoon (October - January) and pre-monsoon (February - May) seasons. Measurements of atmospheric and micrometeorological variables were carried out at three sites covering diagonally the stretch of the Indian Sundarbans (Fig. 1): Jharkhali Island (22° 01' 16" N, 88° 41' 4.75" E) at the confluence of Bidya and Herobhanga River (inner estuary); Bonnie Camp (21° 49' 47.87" N, 88° 37' 22.33" E) almost 30 km downstream (middle estuary) from Jharkhali and Henry Island (21° 34' 27.11" N, 88° 17' 34.06" E) at the southernmost tip of the Sundarbans (outer estuary). The Henry Island site had a 12 m tall tower and the other two sites had 18 m tall towers. The average height of the mangrove patch varied between 5 to 6 m.

The top canopy layer in Henry Island is mainly comprised of *Avicenia officinalis* L., other dominant species in the lower strata are *Aegiceras corniculatum* (L.) Blanco and *Agialites rotundifolia* Roxb.. In the interior parts, *Avicenia alba* Blume and *Bruguiera gymnorrhiza* (L.) Lam. are also found to thrive. In Jharkhali, *Avicenia marina* (Forssk.) Vierh. together with *Excoecaria agallocha* L. dominate the upper canopy, and *Avicenia alba, Phoenix paludosa* Roxb. and *Bruguiera gymnorrhiza* are found in the lower layer. A large abundance of *Phoenix paludosa* is observed in Bonnie camp with few patches of *Aegiceras corniculatum* and *Agialites rotundifolia*.

Experimental methods

In order to observe the diurnal variation, data were logged in hourly intervals for a continuous 24 h cycle. Sampling was conducted for 3 alternate days at each site. Air samples were pumped and passed through LI-840A CO_2/H_2O Gas Analyzer (LI-COR, Inc. USA) at a rate of 1 litre min^{-1} to determine the ambient concentration of CO_2 (in ppm) and that of H_2O (in ppt). To understand the vertical stratification of the atmospheric layer, data were recorded at the same time at heights of 1 m, 5 m, 8 m, 12 m and 15 m in Henry Island and at heights of 1 m, 5 m, 10 m, 15 m and 20 m in Jharkhali and Bonnie Camp. The shorter tower in Henry Island required that flux calculations be made from the difference in concentration at 5 m and 15 m respectively, whereas in the other two stations flux were calculated from the difference between 10 m and 20 m. Micrometeorological parameters including air temperature, atmospheric pressure, relative humidity, wind velocity and its

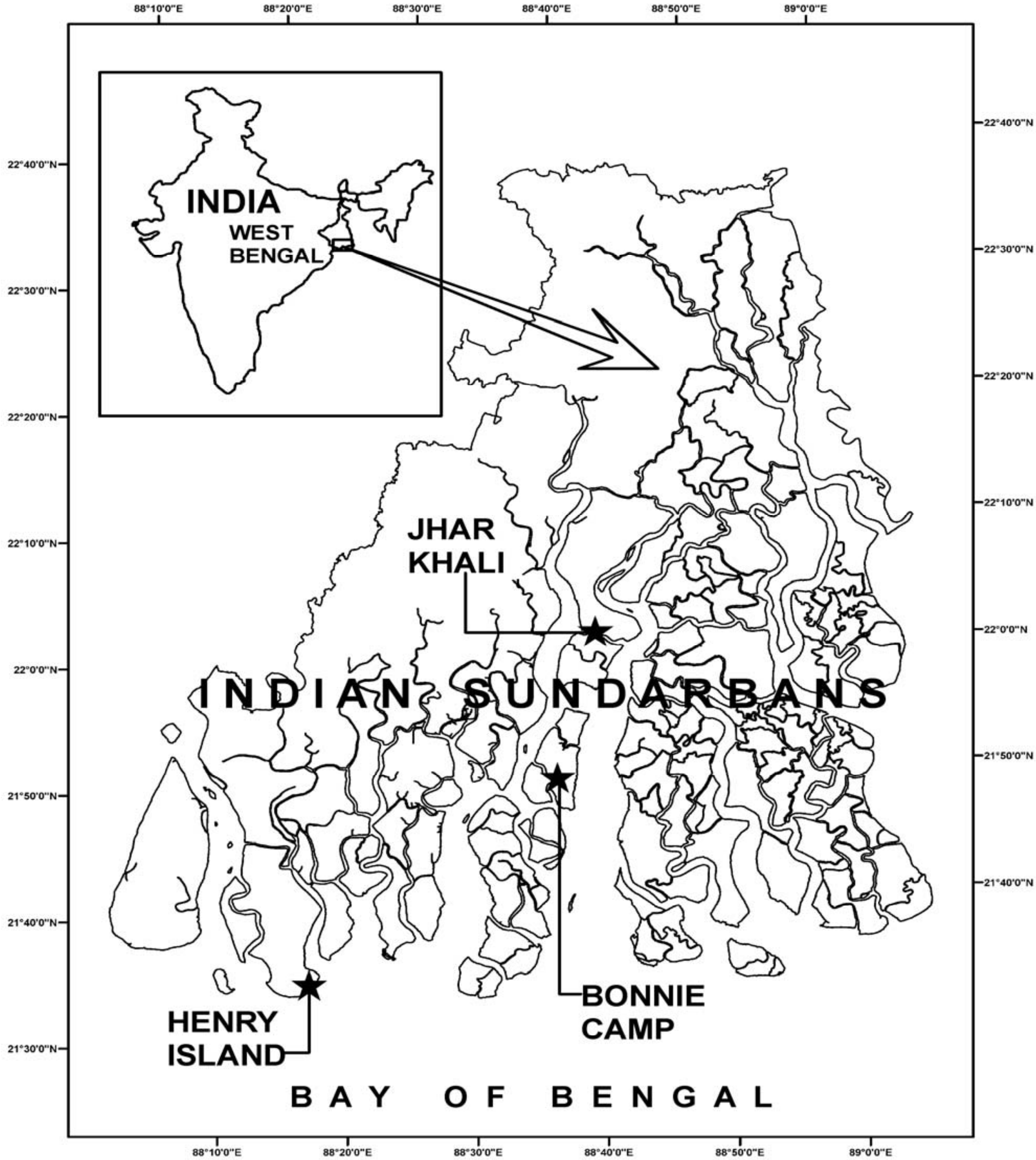

Fig. 1. The location map of Indian Sundarbans showing the three study sites – Jharkhali, Bonnie camp and Henry Island.

direction were recorded with the help of weather stations (WS-2350, La Crosse Technology, USA) mounted at the above mentioned heights.

The CO_2 flux was calculated using the formula

$$FCO_2 = Kc\,\Delta C_i,$$

where, FCO_2 denotes the atmosphere-biosphere flux (mg m^{-2} s^{-1}), ΔC_i is the difference in concentration of CO_2 (mg m^{-3}) at the respective heights mentioned above, and Kc is the exchange velocity. This is defined as

$$Kc = 1/(R_a + R_s),$$

where, R_a and R_s stands for aerodynamic and surface layer resistance, respectively (Barrett 1998). A positive FCO_2 denotes efflux from biosphere to atmosphere, whereas a negative value indicates a biospheric sink.

Surface layer resistance (Rs) was calculated from surface transfer function B^{-1} and friction velocity u_*, following the relations:

$$kB^{-1} = 2(K/D_c)^{2/3}$$

and

$$Rs = B^{-1}/u_*,$$

where, k is the Von Karman constant, K is the thermal diffusivity of air and D_c (molecular diffusivity = 0.115 $(T_2/273)^{1.5}$, where, T_2 is the temperature at 20 m height) (Wesely & Hicks 1977). The friction velocity was calculated using

$$u_* = k(u_{10} - u_{20})/0.693,$$

where, u_{10} and u_{20} are wind speed at 10 m and 20 m height respectively. The equation

$$R_a = (\ln (Z/Z_0) - \Psi_m)/k\, u_*$$

is used to calculate the aerodynamic resistance, R_a, where, Z_0 represents the roughness length and Ψ_m stands for the atmospheric stability correction function (Wesely & Hicks 1977). Z_0 was obtained from the y-intercept ($\ln Z_0$) of the straight line from a plot of ln Z vs. u. The atmospheric correction functions were evaluated based on the output of Z/L, where, L is the Obukhov scale length. It is a metric of atmospheric stability and is approximately the height at which buoyancy starts to dominate over mechanically generated turbulence. The Obukhov scale length was calculated using

$$L = - (u_* \theta_v)/k.g\, (\omega'\theta_v')_s$$

where, θ_v is the mean virtual potential temperature. The potential temperature for air is generally expressed as

$$\theta = T\, (P_0/P)^{R/Cp}$$

where, T is the absolute temperature of the parcel of air, and R and C_p are the universal gas constant and specific heat capacity at constant pressure of air, respectively, P stands for the instantaneous atmospheric pressure, and P_0 is the standard reference pressure taken as 1000 m bar. Using the similarity theory approximation $(\omega'\theta_v')_s = - u_* \theta_*$, where, θ_* is proportional to $\theta_{10} - \theta_{20}$ i.e. the vertical difference in potential virtual temperature, the Obukhov length reduces to

$$L = (u_*^2 \theta_v)/k.g\, \theta_* \quad \text{(Obukhov 1946)}$$

For stable conditions (i.e. $Z/L > 0$), $\Psi_m = 4.7\, Z/L$ and for unstable condition (i.e. $Z/L < 0$), $\Psi_m = - 2 \ln (1 + x)/2 - \ln (1 + x^2)/2 + 2\tan^{-1}(x) - \pi/2$, where, $x = (1 - 15\, Z/L)^{1/4}$ (Stull 1998).

The Richardson number was calculated according to the relation

$$R_i = g/T. (\Delta T/\Delta Z)/(\Delta u/\Delta Z).$$

Under static conditions, i.e. when wind velocity was near zero, the CO_2 flux was evaluated applying the relation of Bowen ratio method based on the energy balance at the ground:

$$FCO_2 = (H + \lambda E)\, dc/ Cp\, (1 +\gamma)\, Tc$$

where, H is sensible heat flux, λ is latent heat of vaporization, E is water vapor flux, dc is the vertical difference in the mixing ratio, γ is the ratio of mean densities of water vapor and air, and Tc represents the effective temperature for sensible and latent heat flux (Mukhophadhya *et al.* 2001).

Sensible heat flux was calculated using

$$H = \rho_t. Cp\, (T_{10} - T_{20})/ (R_a + R_s)$$

and water vapor flux E was computed according to the relation

$$E = \rho_t / (8/5)p\, (P_{H2O(10m)} - P_{H2O(20m)}).$$

The partial pressure of water vapor was calculated using

$$PH_2O = (h/100)\, P_0,$$

where, h is the relative humidity and P_0 is the vapor pressure at a given temperature, obtained from the relation $\ln P_0 = - 0.493048 + 0.07263769t - 0.000294549t^2 + 9.79832 \times 10^{-7}t^3 -1.86536 \times 10^{-9}t$. Latent heat flux was evaluated as per the relation $H_L = EL$, where, L is the latent heat of vaporization. Assuming that 1 mole of CO_2 was photosynthetically converted to 1 mole of carbohydrate; the energy utilized by photosynthetic activity, ΔH_p (W m^{-2}), was evaluated from the 'atmosphere to biosphere' CO_2 flux during daytime (Ganguly *et al*. 2008).

Applying Fick's first law, the molecular diffusion flux was also calculated in the stagnant layers by the relation

$$FCO_2 = - D_d\, dC/dZ$$

where, D_d is the inter-diffusion coefficient for CO_2 and dC/dZ is the concentration gradient along the height (Lerman 1979). D_d was computed using the formula $D_d = 1.325 + 0.009\, t$ (°C).

To identify the layer of frictional influence adjoining the earth's surface, the height of Planetary Boundary Layer (PBL) was calculated using the formula

$$h = 0.25\, u_*/f.$$

given $f = 2\Omega\sin\Phi$ is the Coriolis parameter, Ω and Φ being the rotational speed of the earth and latitude respectively. The dimensionless drag coefficient was calculated by the relation $C_d = u_*^2/u_{10}^2$

Table 1. Range of micrometeorological parameters (minimum – maximum) observed during the study period.

Parameters	Henry Island	Jharkhali	Bonnie Camp
Air temperature (°C) 10 m	26.7-31.3 (5 m)	25.0 -33.4	25.4-33.7
20 m	26.4-32.7 (15 m)	24.7- 33.6	25.0-33.8
Atmospheric pressure (mb)			
10 m	1012-1017	1013-1019	1011-1016
20 m	1012-1017	1013-1020	1011-1017
Wind velocity (m s^{-1}) 10 m	0.7-3.3	0.7-3.2	0.9-5.8
20 m	0.8-4.4	1.3-3.9	2.1-6.8
C_d	21.87- 64.29	17.28-73.52	18.93-66.99
Z_0 (mm)	24.3-496	20.24-606.5	40.76-746
Planetary boundary layer (m)	1623-2973	1623-2705	2164-2705
Solar Radiation (lx)	6700-65000	24700-98200	3950-85000
Relative Humidity (%)	35 -78	32 - 80	40-76
CO_2 Concentration (ppm) 10 m	379.46-402.73	378.82-396.43	379.25-388.01
20 m	384.79-413.5	385.17-399.27	378.82-393.48
FCO_2 (daytime) (mg m^{-2} s^{-1})	0.45-4.04	1.48-7.89	0.11-2.02
-FCO_2 (nighttime) (mg m^{-2} s^{-1})	0.11-3.76	0.36-4.04	0.46-4.63
-ΔH_p (Wm^{-2})	4.09-70.93	1.88-32.56	11.78-135.18
E (daytime) (m mol m^{-2} s^{-1})	0.08-6.77	3.08-14.05	6.33-15.21
E (nighttime) (m mol m^{-2} s^{-1})	0.2-4.93	2.52-5.39	4.99-12.25

(Stull 1998). The solar radiation intensity was measured using a lux meter (LX-105, Leutron, Taiwan).

Leaves from mangrove plants were plucked from the top canopy layer and analyzed for chlorophyll content. Accurately weighed leaf samples were extracted with 80 % acetone solution and their absorbance measured at 645 and 663 nm. Total chlorophyll (a,b) g^{-1} was calculated using the formula

$$(a,b)\ g^{-1} = [20.2(A_{645}) + 8.02(A_{663})] \times V/1000 \times W:$$

where, A denotes absorbance values at the specified wavelength, V is the final volume of chlorophyll extract, and W is the fresh weight of tissue extracted (Witham *et al.* 1971). All the reagents used were of analytical grade.

Results and discussion

Micrometeorological variables

The ranges of micrometeorological (max-min) variables during the diurnal cycle observed at the three sites are given in Table 1. The overall mean air temperatures at the three sites were 29.59 ± 2.57 °C at 10 m and 29.31 ± 2.36 °C at 20 m. A maximum diurnal variation from 25.4 °C to 35.7 °C was observed in Bonnie Camp. In all the three sites the minimum mean temperature (25.7 °C) was recorded around 0300 to 0400 h. The mean atmospheric pressure at the two heights (1014 mb) was also similar. The mean wind velocity above the canopy layer was 2.61 ± 1.31 m s^{-1}. In comparison to the other sites, high wind speed was noticed in Bonnie Camp, with a maximum of 7.8 m s^{-1}. A maximum mean roughness length of 177.9 mm was also observed there, followed by 115.2 mm in Jharkhali and 75.06 mm in Henry Island. High roughness length in Bonnie Camp indicates turbulent mixing did not occur there throughout the entire depth of the canopy, as was reported by Ganguly *et al.* (2008). The mean friction velocity values were higher in Bonnie Camp (0.46 ± 0.09 m s^{-1}) compared to Jharkhali (0.34 ± 0.12 m s^{-1}) and Henry Island (0.36 ± 0.13 m s^{-1}).

The lower values of friction velocity (< 0.25 m s^{-1}) rarely occurred at the sites (< 15 % of the total time), and most of them were recorded during nighttime, similar to what was observed by Pilegaard *et al.* (2001) in a Danish beech forest. The lowest mean drag coefficient (C_d) of 0.024 was registered at Bonnie Camp, followed by Jharkhali (0.032) and Henry Island (0.044). A lower drag coefficient in any fluid environment indicates that objects will experience lesser aerodynamic resistance. Owing to higher friction velocity values, the mean planetary boundary layer was quite high in Bonnie Camp (2142 m), compared to the other two sites. The solar radiation was measured at an interval of 15 minutes and averaged over an hour to correlate with the downward flux. During the peak hours of the day solar radiation varied between 80,000 to 98,000 lx under clear sky, but its value ranged from 24,000 to 38,000 lx when patches of cloud passed by. Almost 30 % of the daytime was obstructed from direct sunlight due to cloud interference. Sometimes giant rainless clouds were found to obstruct direct sunlight for approximately half an hour, accompanied by a fall in air temperature.

Atmospheric stability

According to the stability classes defined by Pasquill (1961) in terms of state of the sky, solar radiation and wind speed, the atmosphere was mostly unstable (between the stability classes of B and D) throughout the diurnal cycle. Stable conditions were observed during the dawn and dusk hours. Inversion of temperature was consistently observed in the three sites between 0000 and 0400 h (Fig. 2). During the evening hours (1600 to 1800) the inversion phenomenon was also observed often. In order to quantify the degree of stability, both the Richardson number (R_i) and Obukhov scale length were calculated using a one-hour time step. R_i was negative during lapse conditions and positive during inversion period as observed by Mukhophadhya *et al.* (2001). During noon hours, maximum instability was exhibited by the atmosphere in all the three sites, with a mean R_i of -1.11. By contrast, the most stable conditions prevailed during late night hours. In Henry Island and Jharkhali the effect of prolonged stable nights continued till morning (0630 h), but in Bonnie Camp lapse conditions started overruling the inversion from the very twilight hours. Neutral conditions were rarely recorded in any of the sites as they were extremely transient. With the change in light condition and increase in temperature, the switch from inversion to lapse condition was rapid.

The Obukhov scale length (L) behaved in the same manner as R_i. During stable hours it showed a positive value, and negative during unstable hours. A maximum, positive value of L was noted in Henry Island (43.82 m) at 0200 h, indicating that at altitudes below this scale length, shear production of turbulence kinetic energy dominates

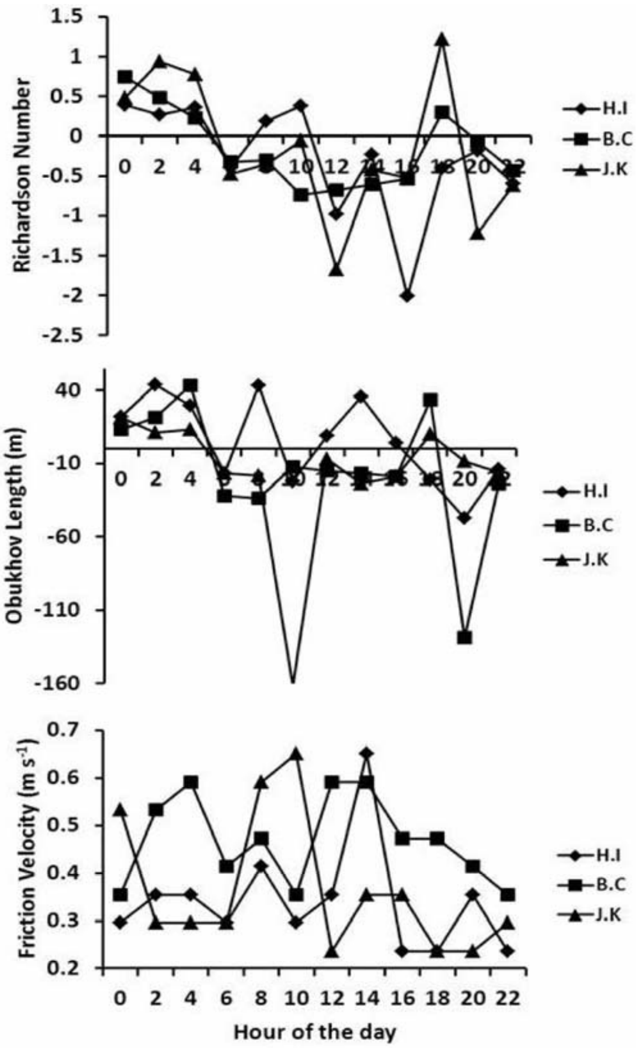

Fig. 2. Observed diurnal variation in Richardson number, Obukhov length and friction velocity (from top to bottom) in the three study sites.

over buoyant production of turbulence (Obukhov 1946). An abruptly negative Obukhov length (-161 m) was recorded in Jharkhali as soon as strong sunlight appeared after a long cloudy phase. This shows that cloud movement may have played a dominant role in controlling atmospheric stability conditions.

Atmospheric CO_2 and H_2O fluxes

The vertical stratification of CO_2 over a 24-h sampling stretch at three sites is illustrated in Fig. 3. In all the sites, the CO_2 concentration at 1 m height, i.e. below the canopy, showed sharp peaks during early evening to night hours, indicating the accumulation of respired CO_2 within the dense canopy. By contrast, the concentration above the

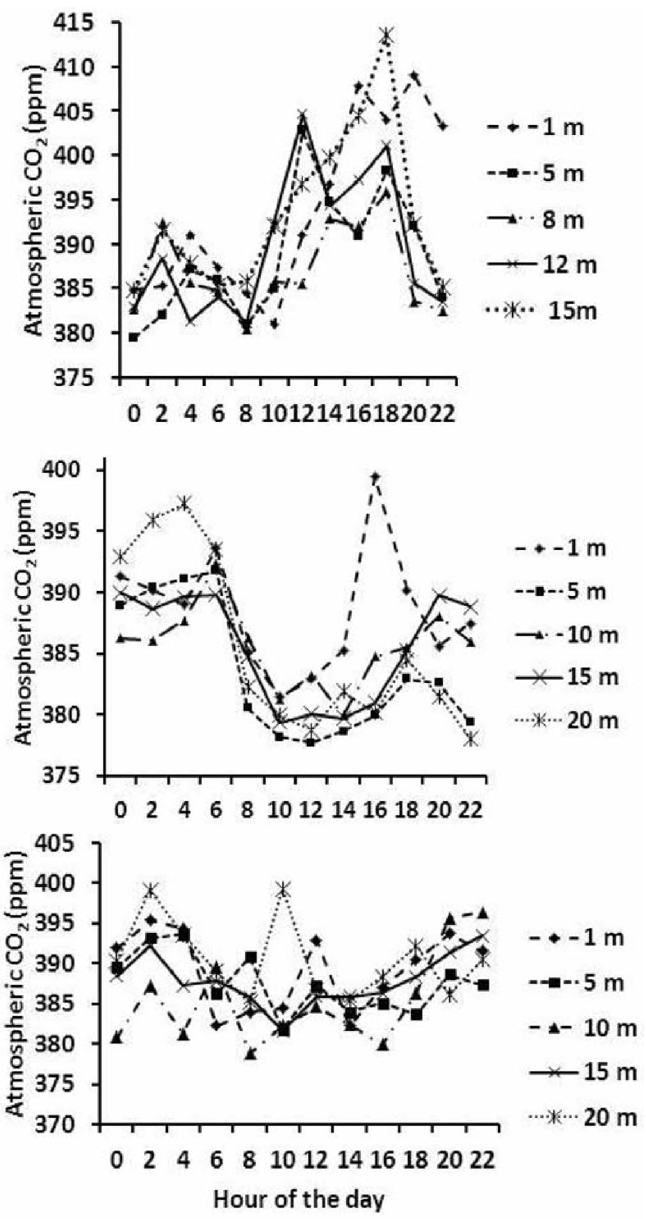

Fig. 3. The vertical stratification of atmospheric CO_2 profile in Henry Island, Bonnie Camp and Jharkhali (from top to bottom).

canopy exhibited different trends at the three sites. In Henry Island a steadily increasing CO_2 mixing ratio was noted in this layer, whereas in Bonnie Camp it was lower than that under the canopy. In Jharkhali, the CO_2 concentration above the canopy was almost constant throughout the diurnal cycle. The mean (± standard deviation) daytime CO_2 concentration in Henry Island, Jharkhali and Bonnie Camp was 380.91 ± 2.70 ppm, 373.76 ± 2.66 ppm and 375.76 ± 2.14 ppm respectively, while at nighttime was 390.02 ± 4.17, 387.67 ± 1.36 and 390.48 ± 1.99 ppm respectively. A mean decrease of 3.65 % in CO_2 concentration during daytime compared to nighttime was observed.

The ecosystem exchange of CO_2 is primarily controlled by two types of fluxes: at daytime, the influx of CO_2 from biosphere to atmosphere (due to photosynthetic activities by green plants), with the reverse conditions prevailing during nighttime due to plant and soil respiration (Aubinet *et al.* 2005). The computation of fluxes by micrometeorological techniques is known to underestimate fluxes during calm and stable conditions. In order to avoid this, data were considered only in those instances, when u_* was observed to be greater than 0.25. The sink activity (i.e. negative flux) is noticed from 0730 h onwards in Jharkhali and Henry Island, whereas in Bonnie Camp neutral conditions were observed around 0530 h and by 0615 h negative flux became prominent accompanied by a rapid switch over from inversion to unstable conditions as mentioned above. Generally the magnitude of nighttime positive flux is smaller than that of daytime negative flux (Mildenberger *et al.* 2009) if the ecosystem on the whole is a net autotrophic one. The trend of diurnal variation of CO_2 flux is given in Fig. 4. In Henry Island and Jharkhali the mean daytime flux varied between -0.45 to -4.41 mg m^{-2} s^{-1} (10.22 to 100.22 μmol m^{-2} s^{-1}) and -1.48 to -7.89 mg m^{-2} s^{-1} (15.68 to 179.31 μmol m^{-2} s^{-1}), respectively. Both the areas exhibited net sink strength of 18.94 and 51.06 g m^{-2} d^{-1}, respectively. Ray *et al.* (2011) have observed a net community CO_2 exchange of 86.4 ± 57.02 g m^{-2} d^{-1} in the same arena of Sundarbans. By contrast, in Bonnie Camp the daytime influx ranged between -0.11 to -2.02 mg m^{-2} s^{-1} (2.5 to 45.9 μmol m^{-2} s^{-1}) and nighttime respiration varied from 0.46 to 4.63 mg m^{-2} s^{-1} (10.45 to 59.09 μmol m^{-2} s^{-1}). The net flux observed in Bonnie Camp was almost neutral, with a mild mean sink strength of 1.51 g m^{-2} d^{-1}. Amongst all other micrometeorological variables, the response of flux was most prominent with the variation of solar radiation (Fig. 5). Although, Jarvis *et al.* (1985), Baldocchi (1997), Hollinger *et al.* (1994) and Ruimy *et al.* (1995) have stated that canopy photosynthesis is more efficient under cloudy skies, in all the three sites a decreased flux was observed under giant cloudy patches. This is may be because, as Hollinger *et al.* (1994), among others, reported that ecosystem uptake of CO_2, is enhanced when the fraction of diffuse to total radiation increases. In our case, the monsoon cloud has adequately reduced the light condition instead of scattering diffused radiation.

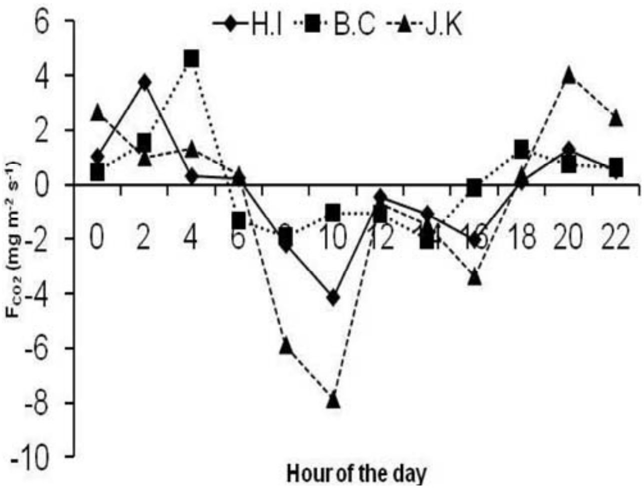

Fig. 4. Diurnal variation of atmosphere-biosphere CO_2 flux in all three sites.

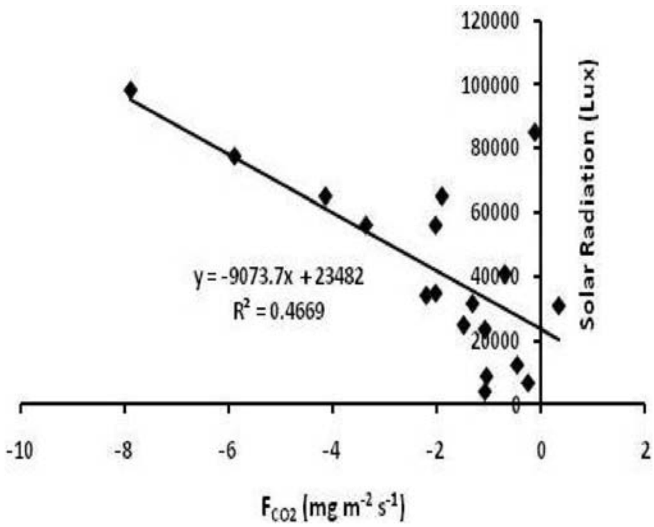

Fig. 5. The correlation between solar radiation and biosphere-ward influx of CO_2 during daytime.

In addition to reducing the light intensity to a great extent, the passing cloud also produced a sharp decrease in temperature. During our study in Bonnie Camp, interference by cloud cover during both day and night was maximum, which might have lead to decreased photosynthetic activity and hence lesser 'atmosphere to biosphere' CO_2 flux in this site compared to others.

Analysis of the chlorophyll content in the leaves of 5 dominant mangrove species was carried out (Table 2). Amongst the species of *Avicenia, A. officinalis* had the highest total leaf chlorophyll (1.29 mg g^{-1}) followed by *A. marina* (0.296 mg g^{-1}) and *A. alba* (0.106 mg g^{-1}). *Excoecaria agallocha* on the other hand had a total chlorophyll concentration of 0.151 mg g^{-1}. The lowest chlorophyll content (0.071 mg g^{-1}) was found in *Phoenix paludosa*, the dominant species in Bonnie Camp. Nandy & Ghose (2001) have observed that the photosynthetic assimilation rate of *Phoenix paludosa* was much less than *Avicenia officinalis*, *Avicenia marina* and *Excoecaria agallocha*. Thus apart from cloud cover, lower leaf chlorophyll content in the abundant species could be another reason for the reduced sink strength in Bonnie Camp.

Table 2. Fragmented leaf chlorophyll concentration of five dominant mangrove species.

Species	Chlorophyll (mg g^{-1})	
	Chl-a	Chl-b
Avicenia officinalis	0.770	0.400
Phoenix paludosa	0.027	0.031
Avicenia alba	0.069	0.026
Excoecaria agallocha	0.092	0.047
Avicenia marina	0.186	0.088

The ecosystem exchange of water vapor is the sum total of the transpiration by plant bodies and evaporation of intercepted fog and rain, corrected for the surface condensation of water vapor (Meiresonne *et al.* 2003). Apart from Henry Island, in the other two sites a positive water vapor flux was registered through a 24 - h cycle (Fig. 6). Transpiration and photosynthetic CO_2 exchange are known to be strongly coupled process - i.e. a CO_2 intrusion is always associated with a vapor outflow (Mildenberger *et al.* 2009). We observed significant difference in the mean CO_2 flux of Jharkhali and Bonnie Camp but the water vapor fluxes in both the sites were comparatively similar. This makes us hypothesize that evaporation overrules transpiration and contributes the most to water vapor flux, as observed by Mildenberger *et al.* (2009). A mean daytime water vapor flux (E), averaged over three sites, of 7.83 ± 4.95 m mol m^{-2} s^{-1} and a nighttime flux of 3.38 ± 3.32 m mol m^{-2} s^{-1} was noted. A similar increased evaporation rate during the daytime was observed by Ganguly *et al.* (2008). In Henry Island the daytime mean water vapor flux was also observed to be much less compared to the other two sites. The Bowen ratio - calculated from the ratio of sensible and latent heat flux - had a mean daytime value of 0.71 and a nighttime value of -0.89, further justifying the

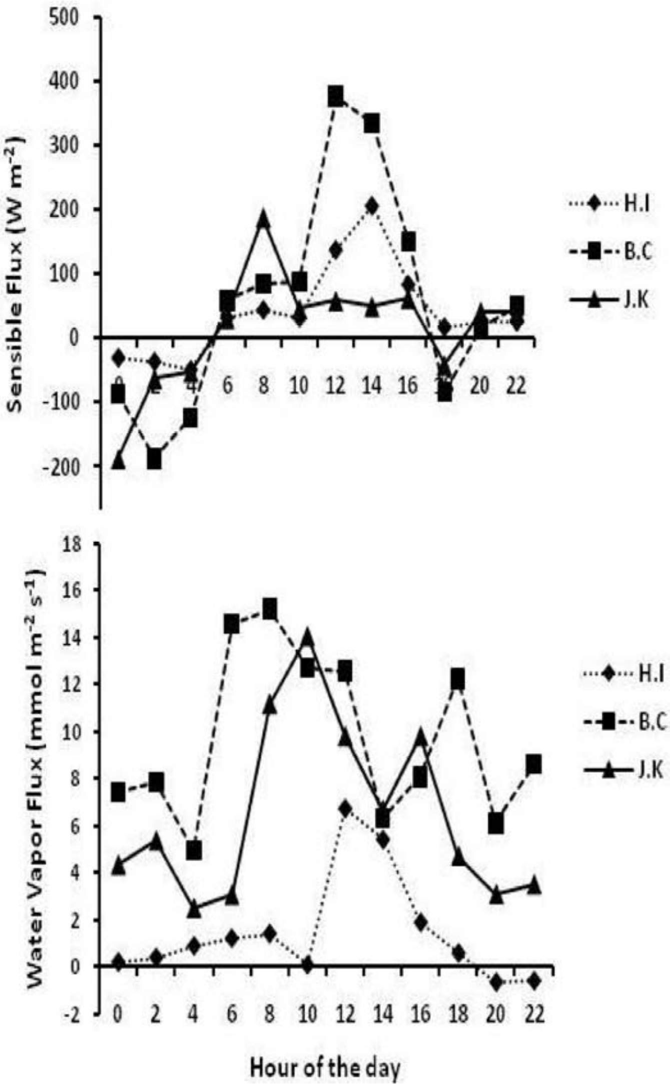

Fig. 6. Diurnal variation of sensible heat flux and water vapor flux in the three sites.

diurnal variation of evaporation rate. The Bowen ratio values reflect that a greater portion of available surface energy is dissipated to the atmosphere as latent heat than sensible heat. The mean energy consumed by photosynthesis (ΔH_p) was found maximum in Jharkhali (-24.2 W m^{-2}) (Fig. 7). This shows that the maximum utilization of incoming solar radiation and hence sequestering CO_2 molecules in the form of carbohydrate took place in the site Jharkhali.

On the whole it can be concluded that the terrestrial compartment of the study site acted as a net autotrophic ecosystem, although, the sink strength varied spatially. Amongst the atmospheric parameters solar intensity was found to play a decisive role in determining the flux magnitude. The leaf chlorophyll content of the dominant species of the study sites may also influence the degree of biochemical CO_2 sequestration. From the observed difference in water vapour flux, between day and nighttime, it can be further inferred that evaporation prevails over transpiration in all the three sites.

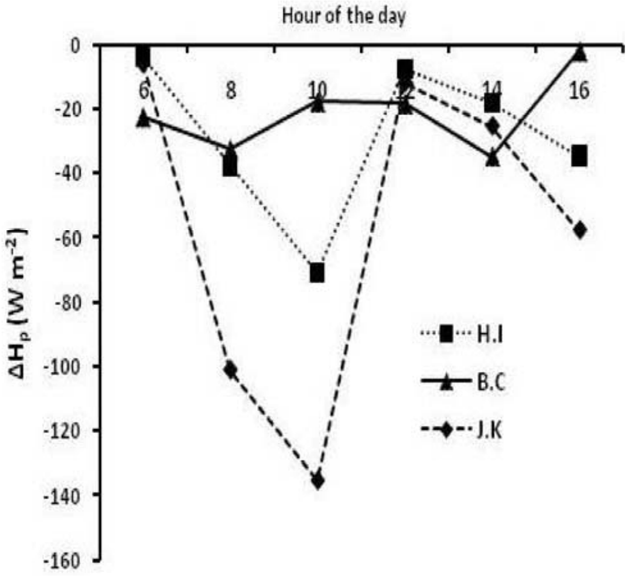

Fig. 7. Diurnal variation in energy consumed by photosynthesis (ΔH_p) in the three sites.

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