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Monsoonal Influence on Evapotranspiration of the Tropical Mangrove Forest in Northeast India

Dipnarayan Ganguly, Raghab Ray, Natasha Majumder, Chumki Chowdhury, Tapan Kumar Jana

Department of Marine Science, Calcutta University, Kolkata, India
Email: tkjana@hotmail.com

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Abstract

Evapotranspiration (ET) is an important part of the water cycle. This study reports on the monsoonal influence on the temporal variation in evapotranspiration of an extremely water conservative and salinity stressed tropical mangrove forest at the land-ocean boundary of northeast coast of India. The magnitude and dynamics of evapotranspiration (ET) exhibited seasonality dominated by monsoon and evaporation rate was greater ($0.055 \pm 0.015\ g \cdot m^{-2} \cdot s^{-1}$) during the monsoon than in pre-monsoon ($0.049 \pm 0.018\ g \cdot m^{-2} \cdot s^{-1}$) and post-monsoon ($0.044 \pm 0.012\ g \cdot m^{-2} \cdot s^{-1}$). Seasonal difference in evapotranpiration was mostly due to fluctuation of canopy resistance, which was the minimum during monsoon when relative humidity was greater than in the dry season (pre- and post-monsoon) and deficiency of water supply ($ET \approx ET_{eq}$) was minimum. Evapotranspiration in the Sundarban mangrove ecosystem is the predominant biophysical processes that recycles 67.7% of total precipitation annually to the atmosphere, and has significant monsoonal influence.

Keywords

Canopy Resistance, Evapotranspiration, Hydrological Cycle, India, Mangrove Forest, Monsoonal Cycle

1. Introduction

Water vapour plays an important role in the hydrologic cycle, which describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere. The loss of water from plant cells to the atmosphere by vaporization is called transpiration. More than 80% of the water that enters plants through

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their roots returns to the atmosphere through this process [1]. Low water vapour pressure in the air relative to that inside the leaves is the major driving force for water loss from leaves, which drives the movement into leaves and in turn drives movement into plant roots. Evapotranspiration is the main biophysical process that maintains the availability of water vapour in the atmosphere. Over the entire land surface of the globe, rainfall averages around 750 mm·y^{-1}, of which some two third is returned to the atmosphere as evapotranspiration, making evapotranspiration the largest single component to study the terrestrial hydrological cycle [2].

The importance of evapotranspiration (ET) in the hydrologic cycle generally increases with increasing aridity [3]. In arid and semi-arid climates, ET often consumes a large part of precipitation and the amount and timing of ET can strongly affect stream flow and groundwater recharge [3] [4]. Priestley and Taylor [5] suggested to compare ET with equilibrium evapotranspiration (ETeq, defined as evaporation from a wet surface into saturated air) in order to assess the effect of water availability. It is of interest to study the key factors affecting evapotranspiration of vegetation in an ecosystem in the perspective of the key global change issue [6], especially for the seasonal transition periods [7] [8]. Large variability in annual rainfall totals has been observed in the tropics and is thought to be influenced by El Nino-Southern Oscillation (ENSO) and other anomalous circulations [9]-[11]. This in turn affects the amounts of water available for evapotranspiration, affecting local hydrology [12]-[14]. The erratic monsoon was a result of cyclone Aila, which devasted parts of West Bengal and Orissa on May 25, 2009, weakened the monsoon flow. This situation further deteriorated due to the high pressure area over central Asia, which blocked weather systems that brings rain to India, resulting only 77% rainfall of the long period average (LPA).

Evapotranspiration, just as precipitation, is subject to variability in space and time. And some recent estimates of India's evapotranspiration [15]-[18] are subject to uncertainties and underestimation [19]. During the failure of monsoon with below-normal rainfall evapotranspiration could be in greater magnitude [20], implying correspondingly reduced availability of water amenable for human use. Therefore, the discrepancy of the result in the measurement of India's evapotranspiration merit reconciliation through further studies, considering the importance of the water budget in the nation's natural resource context. India's land area is 3.28 million km^2 [21] with varying a real extent, climatic regions, and landscape characteristics. This requires the measurement of evapotranspiration taking into account of spatial and temporal variation in order to integrate the overall estimate, and hence to provide a credible revised estimate of India's evapotranspiration.

Mangrove ecosystem in tropical and sub-tropical environment is water limited ecosystem where the exchange of water between biosphere and atmosphere is restricted to a great extent by monsoonal activities. In the seasonally water-limited systems such as Savana, nature of the biosphere-atmosphere interactions changes during monsoon [22]. In the tropics and sub-tropics, mangrove cover around 1.0 ×10^5 to 2.3 × 10^5 km^2 of area and is one of the major ecosystem fringing 60% - 75% of the tropical coasts [23]. It is of interest to study the contribution of mangrove to recycle the fraction of total rainfall by evapotranspiration. Attempts have been made here to study the seasonal variation of water vapour exchange in relation to the environmental variables at the land-ocean boundary of Sundarbans.

2. Material and Methods

2.1. Study Area

The Indian Sundarban Mangrove forest in the estuarine phase of the river Ganges covers an area of 9630 km^2 out of which 4264 km^2 is under reserve forest. It is the largest delta on the globe (world's heritage site, whc.unesco.org/en/list/452) and a unique bioclimatic zone for its biodiversity of mangrove flora and fauna both in land and in water at the land-ocean boundary of the Sundarban mangrove forest along the of Bay of Bengal (20˚32' - 20˚40' N and 88˚05' - 89˚E). This land-ocean boundary is highly irregular and criss-crossed by several rivers and waterways. East to west this area is about 140 km from the east boundary to the west boundary and 50 - 70 km from the shoreline to the north boundary. There are over 110 discrete islands and low-lying intertidal zones of which 54 have been reclaimed by human population and the remaining 56 are marked for reserve forest including tiger reserve [24]. The islands inside the reserve forest are covered with thick mangrove forest. Height of mangrove plants greater than 10 m is rare. Mangroves namely *Avicennia officinalis*, *Avicennia alba*, *Avicennia marina* and *Aegiceras* sp. are the dominant species. *Excoecaria agallocha* and *Heritiera fomes* are thinly distributed and *Ceriops decandra* is found scattered all over the island. *Heritiera fomes* (locally called Sundari, from which Sundarban derives its name), abundant on the Bangladesh side is not common on the Indian side where it is considered endangered [25].

The deltaic soil of Sundarban Biosphere Reserve comprises mainly with saline alluvial soil consisting of clay, silt, fine sand and coarse sand particles.

Mangrove species are grouped together as they share specialized physiological and ecological adaptations to the challenging inter-tidal conditions on tropical and subtropical coasts. "Mangrove" is therefore an ecological grouping rather than reflecting any consistent taxonomic affinity [26].

2.2. Climate

Indian climate is a manifestation of the seasonal change in the position of the ITCZ from about 10˚S over north Indian Ocean in January to about 25˚N, over Asia in July. In the northern winter, the air over Southern Asia is cooler and denser than air over the ocean, and so, the surface atmospheric temperature is greater over the continent than over the ocean, resulting pressure gradient levels to a northerly or northeasterly flow of air from Asia to south of the equator. This flow of air is northeast monsoon. As the year progresses, increased heating weakens the high pressure over Southern Asia. By the northern summer low has developed, so that from May/June to September a southerly or southwesterly wind blows across the region. This is the southwest monsoon (summer monsoon), the stronger of the two monsoons. Four month gap from February to May are called pre-monsoon.

The seasonal climate in Sundarban may be conveniently categorized into pre-monsoon (February to May), monsoon (June to September), post-monsoon (October to January). High humidity prevails (~98%) during summer monsoon season. The annual mean maximum and minimum temperature are 31.2˚C and 13.7˚C, respectively. The total annual rainfall is about 1500 - 2000 mm. Most of the rainfall (about 74% of the total) occurs during the southwest monsoon period. Cyclonic storms occur sometime in April but frequently associated with monsoon rainfall in July-August. Measurements were carried out at two sites: one located at the Lothian Island (Station 2, 22.420˚N and 88.420˚E) in the confluence of Saptamukhi River and Bay of Bengal, and the other one at Sajnekhali (Station 1, 22.117˚N and 88.82˚E) located at a distance of 117 km from Lothian Island (approximately 38 km^2 area) (**Figure 1**).

To determine any spatial variation within the mangrove forest these two stations were selected near the west

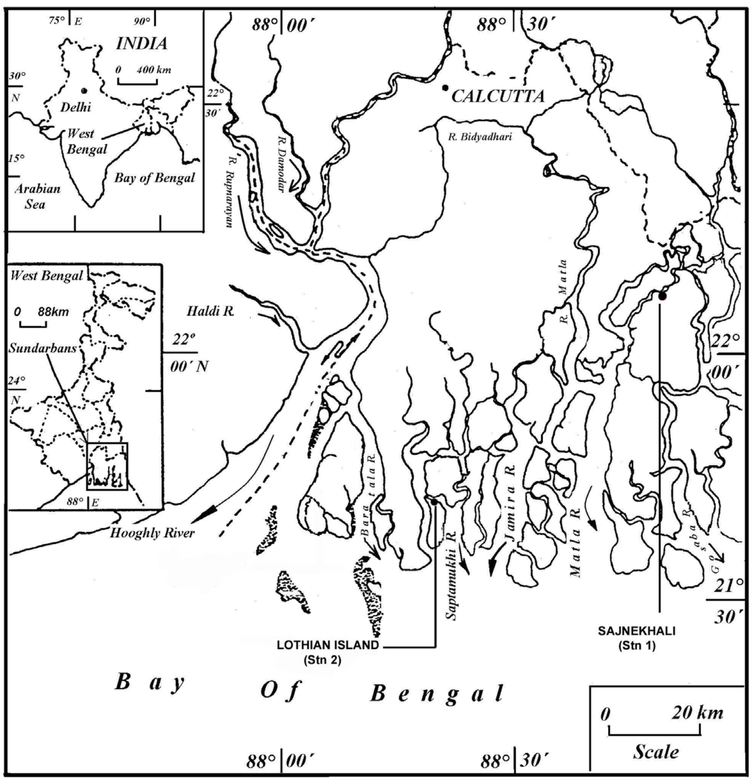


Figure 1. Location of the two selected stations in the Indian Sundarban Mangrove forest.

ern (Station 2) and eastern margins (Station 1) of Indian Sundarban. In order to measure evapotranspiration and some other related parameter, micrometeorological data were collected from the field. For this purpose two towers were selected, both situated in the midst of a deep forest (fetch up to 10 km) so that the true signature of mangrove could be examined. The towers (each about 25 m tall) over the mangrove forest stands at both sites were used for the measurements at 10 and 20 m. The northern part of Lothian is newly formed and shallow, which is inundated twice a day regularly, whereas the southern part of the island is gradually elevated and inundated only during spring tide.

2.3. Measurement of Water Vapour and Related Parameters

Monthly variations of meteorological parameters like air temperature, atmospheric moisture content, atmospheric pressure and wind velocity at these stations were recorded simultaneously at two different heights (10 m and 20 m) during 2006-2008 by using probes and an anemometer connected with computerized weather station (Model No. Davis 7440). Climate sensors were scanned in every 5 min and 1hr average were recorded.

2.4. Equations

Following equations were used to calculate:

a) The partial pressure of water vapour [27]:

$$P_{\mathrm{H_2O}} = (h/100)P_0 \tag{1}$$

where h is relative humidity.

b) P_0, vapour pressure of water (kPa) at a given temperature (˚C) [27]:

$$\mathrm{Ln}P_0 = -0.493048 + 0.07263769T - 0.000294549T^2 + 9.79832\times10^{-7}T^3 - 1.8653\times10^{-9}T^4 \tag{2}$$

c) The rate of evapotranspiration (mg·m^{-2}·s^{-1}) (Pal Arya, 2001):

$$Et \text{ or } E = \left[\frac{\rho_t}{1.6\times p}\times\frac{\left[\left(P_{\mathrm{H_2O(10\,m)}} - P_{\mathrm{H_2O(20\,m)}}\right)\right]}{(r_a + r_s)}\right] \tag{3}$$

where, ρ_t is the density of air, p is atmospheric pressure. In order to express evapotranspiration in terms of MJ m^{-2}·s^{-1}, ET (mg·m^{-2}·s^{-1}) was multiplied by λ, where λ = latent heat of vaporization = 2.45 MJ·Kg^{-1}.

d) Latent heat flux (W·m^{-2}) [28]:

$$HL = ET\times\lambda \tag{4}$$

e) Canopy resistance (r_c) (in s cm^{-1}) [29]

$$r_c = \left[\rho_t c_p (e_s - e_d)/(\gamma\times ET)\right] + r_a\left[\frac{\Delta}{\gamma\left(\frac{A}{ET}-1\right)} - 1\right] \tag{5}$$

where, A = available energy for evapotranspiration: (R_n – H_G – H_s) (W·m^{-2}), c_p = specific heat of moist air (J·kg^{-1}·K^{-1}), e_s = saturation water vapor pressure at height d (mb), e_d = water vapor pressure at height d (mb), R_N = net solar radiation (W·m^{-2}), H_S = storage heat energy (W·m^{-2}), Δ = slope of the saturation water vapor pressure curve (mb·K^{-1}), γ = psychometric constant (66.5 Pa·K^{-1}).

f) Equilibrium evapotranspiration (ET_{eq}, MJ·m^{-2}·d^{-1}) defined as evaporation from a wet surface into saturated air [30] and the ratio of sensible (H) and latent heat (H_L) flux (Bowen ratio, β) = H/H_L [5]:

$$ET_{eq} = \Delta(R_N - H_G)/(\Delta+\gamma) \tag{6}$$

R_N = net solar radiation (W·m^{-2}), incoming net short wave radiation (0 < R_N ≤ 4 μm) was obtained from HY-SPLIT model (http://www.arl.noaa.gov/ready.html).

H_G = ground heat flux (W·m^{-2}), Δ = slope of the saturation water vapour pressure curve (mb·K^{-1}), γ = psychrometric constant (66.5 Pa·K^{-1})

g) r_a = aerodynamic resistance (s·cm^{-1}) [31]:

$$r_a = \left\{\ln\left(\frac{z}{z^0}\right) - \varphi_c\right\}\left(ku^*\right)^{-1} \tag{7}$$

where φ_c = correction function for atmosphere stability [31], u^* = frictional velocity.

h) H, sensible heat flux (W·m^{-2}) [28]

$$H = \left\{\rho_t c_p \left(T_{10\text{ m}} - T_{20\text{ m}}\right)\right\}\left(r_a + r_s\right)^{-1} \tag{8}$$

where ρ_t and c_p = density and specific heat of air respectively.

i) r_s, surface layer resistance = $B^{-1}/\left(u^*\right)$ (9)

where $B^{-1} = 2(K/D_c)^{2/3}k^{-1}$, where k = Von Karman constant, K = thermal diffusivity of air, D_c = molecular diffusivity [32].

j) H_G, ground heat flux (W·m^{-2}) = $-K\left(\mathrm{d}T/\mathrm{d}z\right)$ (10)

where K = thermal conductivity of soil, dT/dz = downward temperature gradient of the soil [28].

k) The slope of the saturation vapour pressure curve: Δ = slope of the saturation vapour pressure curve (kPa·˚C^{-1}) at T_{mean}: [33]:

$$\Delta = \frac{4098\left[0.6108\exp\left(17.27T_{\text{mean}}/\left(T_{\text{mean}} + 237.3\right)\right)\right]}{\left(T_{\text{mean}} + 237.3\right)^2} \tag{11}$$

T_{mean} = daily mean air temperature at 2 m height [˚C].

l) Saturation vapour pressure, e_s in kPa [34]:

$$e_s = \exp\left[\left(16.78T - 116.9\right)/\left(T + 237.3\right)\right] \tag{12}$$

m) Actual vapour Pressure $\left(e_d\right)$

$$e_d = e_s \times RH/100 \tag{13}$$

where, RH = relative humidity in percent

n) Vapour Pressure Deficit [35],

$$VPD = e_s - e_d \tag{14}$$

o) Planetary boundary layer [36]

$$PBL = 0.25u^*/f \tag{15}$$

where, f is Coriolis parameter related to the rotational speed (Ω) of the earth and latitude (φ) as $f = 2\Omega\sin\varphi$.

3. Result and Discussion

3.1. Temperature

The climate of the Indian subcontinent is dominated by mainly southwest monsoon that causes regular changes in atmospheric temperature, wind speed, direction, rainfall, humidity, air pressure, etc. These changes in the micrometeorological conditions often become the regulating factor behind various biophysical processes in the surface. Highest air temperature at 10 m height was obtained during May with a mean value of 32.27˚C ± 0.85˚C where as the lowest values were obtained during December with a mean value of 21.51˚C ± 4.57˚C (**Table 1**). On average the mean annual daytime temperature was recorded 11.4% higher than that of nighttime. The minimum PBL height of 2095 m was observed during post-monsoon accompanying with the lowest temperature and humidity in the atmosphere compared to that of the monsoon and pre-monsoon. The ratio of roughness length (Z^0 = 4.91 – 6.46 m) to the average height of the mangrove plant (h^0 ≈ 10 m) varied between 0.49 and 0.65. The high roughness length indicates that turbulent mixing did not occur throughout the entire depth of the canopy providing an inefficient surface-atmosphere coupling for the exchange of heat and energy transfer.

Table 1. Monthly variation of different micrometeorological parameters during the study period (2006-2008). Values are the average of the measurements from the two stations.

Seasons	Temp. (˚C)		Wind (m/sec)		Humidity (%)	Pressure (mm)	Wind direction
2006	10 m	20 m	10 m	20 m	10 m	10 m	
Pre-monsoon	29.63 ± 2.01	28.7 ± 2.23	2.83 ± 2.6	4.18 ± 2.61	80.86 ± 8.22	754.66 ± 9.27	25˚ - 225˚
Monsoon	29.44 ± 2.79	28.81 ± 2.84	1.65 ± 0.16	2.31 ± 0.14	88.41 ± 14.22	755.08 ± 7.01	135˚ - 270˚
Post-monsoon	24.74 ± 4.70	24.3 ± 4.51	1.03 ± 1.25	2.02 ± 0.97	74.66 ± 9.88	761.09 ± 4.63	340˚ - 90˚
2007							
Pre-monsoon	30.51 ± 3.94	29.51 ± 1.58	3.13 ± 2.18	4.35 ± 2.34	83.39 ± 7.9	754.42 ± 9.12	25˚ - 225˚
Monsoon	29.80 ± 2.51	29.13 ± 4.69	1.39 ± 0.46	1.97 ± 0.84	89.13 ± 9.84	756.51 ± 8.88	135˚ - 270˚
Post-monsoon	23.31 ± 4.68	22.35 ± 5.86	1.25 ± 0.92	2.06 ± 0.91	75.03 ± 7.14	759.85 ± 7.7	340˚ - 90˚
2008							
Pre-monsoon	30.42 ± 2.88	29.51 ± 2.24	3.61 ± 2.36	4.76 ± 2.85	81.82 ± 9.12	754.37 ± 4.46	25˚ - 225˚
Monsoon	29.92 ± 2.60	29.28 ± 4.82	1.37 ± 1.8	2.13 ± 2.08	83.24 ± 10.32	755.99 ± 8.88	135˚ - 270˚
Post-monsoon	22.91 ± 4.32	22.01 ± 4.69	0.81 ± 0.38	1.68 ± 0.15	72.45 ± 5.91	761.64 ± 6.36	340˚ - 90˚

A diurnal maximum temperature difference of 13.0˚C was observed in December and a minimum of 3.9˚C in June. Though inversion of temperature was observed in the mangrove forest in the midnight between 00:00 and 04:00 h during pre-monsoon and post-monsoon seasons, it was a rare phenomenon in the monsoon.

3.2. Wind and Pressure

Annual shift of ITCZ in the tropical mangrove forest (e.g. Sundarban) results a significant change in wind direction, velocity and composition. This could cause seasonality in the mixing ratios of various trace gases in the mangrove environment. Southwest monsoon was more intense with respect to its extreme character relative to the north-east monsoon in this micro-climatic region. Highest wind speed was recorded during April with a mean value of 5.37 ± 0.78 $m \cdot s^{-1}$ (**Table 1**). The onset of post-monsoon brings relatively cool and calm condition with lesser humidity in the air in this climatic zone. The average atmospheric pressure ranged between 748.5 and 763.68 mm Hg with few low pressures spells from May to August. Diurnal distribution of wind velocity showed two peaks, the first around 12:00 hr local time and the second around late night time.

The wind in the lower atmosphere plays a major role in regulating various bio-physical processes both in terrestrial as well as aquatic ecosystems. It exerts a force on the surface over which it blows, it is effective in transporting heat and material from the surface and it is highly variable in space and time.

Direction of wind changes with seasons. During the pre-monsoon the wind was blown both from the land and seaward direction within the range of 25 - 600 (northeast)-90˚ (east)-225˚ (southwest). Humid wind was blown consistently from the seaward direction which ranged between 135˚ and 270˚ (southeast to southwest) throughout the months of monsoon. In the months of post-monsoon wind was mainly blown from the landward direction, which ranged between 270˚ (west)-315-345˚ (northwest)-60-90˚ (northeast-east) (**Table 1**). The dry wind blowing from the landward direction supports advective transport of different pollutants (including different trace gases) to the mangrove atmosphere. Land breeze-sea breeze phenomenon was present only in the months of post-monsoon and early pre-monsoon. Rest part of the year this phenomenon was totally suppressed by monsoonal wind.

The mangrove atmosphere remained unstable [stable condition is for $0 < z/L < 1$ and $0 > z/L > -1$ is unstable condition], which favored turbulent mixing and transport of both heat and momentum within the boundary layer for most part of the year. Few spells of atmospheric stability were recorded all of which were observed during the nighttime of late post-monsoon and pre-monsoon seasons.

3.3. Humidity

Due to the presence of the open ocean near these sampling stations the humidity values did not vary very much and the monthly mean humidity never went below 60% throughout the year. The humidity was at a higher range (84.17% - 96.39%) during the monsoon than in the pre- (76.47% - 77.95%) and post-monsoon (69.56% - 79.95%). Intensity and availability (seasonal) of solar radiation control the humidity of the troposphere. The diurnal pattern of humidity showed higher variation during the months of post-monsoon in consistence with temperature relative to that of rest of the seasons.

3.4. Rainfall

Sundarban mangrove ecosystem regularly experiences a large amount of rainfall, which is mainly attributed to the monsoon starting from June, and extends up to September (sometimes up to October) of every year. This southwest monsoon carries a huge amount of humid air from the ocean to the terrestrial area, causing substantial rainfall in this Indian subcontinent. Monthly rainfall data for the study area was collected from the Indian Meteorological Department (http://www.imd.gov.in/). Highest annual rainfall was recorded in 2007 with a value of 2252.9 mm. On the other hand the year 2008 was the driest during the study period with a yearly rainfall value of 1622.3 mm. The post-monsoon season (October to January) was relatively dry (due to the north-east monsoon carrying cold and dry air from the terrestrial land mass) with respect to the rest of the year. There was almost no rainfall recorded in December during the study period.

3.5. Evapotranspiration

Daily incoming short wave radiation ranged from 0 (night time minimum) to 688 $W \cdot m^{-2}$ (day time maximum) during the measurement period with an annual daytime mean of 435 ± 32.8 $W \cdot m^{-2}$. The distribution of incoming net short wave radiation was found to be 0.29 R_N for sensible, 0.35 R_N for latent heat, 0.04 R_N for ground heat flux, suggesting that latent heat flux greater than the sensible heat flux (H) [35] [36]. Latent heat flux showed significant positive correlation with R_N (HL = 0.1738 R_N + 61.418, R^2 = 69.5%, $p < 0.01$ for the pre-monsoon, HL = 0.2119 R_N + 67.684, R^2 = 71%, $p < 0.001$ for the monsoon, HL = 0.153 RN + 81.455, R^2 = 61%, $p < 0.01$ for the post-monsoon). Average annual precipitation (P) was 2065 ± 194.1 mm, of which around 87% occurred from June to October (Monsoon). Total evapotranspiration during monsoon months were estimated to be 477.57 mm with a rate 0.055 $g \cdot m^{-2} \cdot s^{-1}$ which was greater than in the post-monsoon (469.44 mm and 0.040 $g \cdot m^{-2} \cdot s^{-1}$) and the post-monsoon (457.58 and 0,044 $g \cdot m^{-2} \cdot s^{-1}$) (**Figure 2** and **Figure 3**). The ratio of ET to P (67.7%) at the land ocean boundary demonstrated that the magnitudes of ET and P were not equal on an annual basis. This ratio is low as compared with that of steppe in central Mongolia (79% - 94%) [37], and that for a steppe close to the edge of the Eurasian cryosphere in Mongolia (94%) [38] [39]. However, the ET to P ratio in this study was found to be close to the ratios reported for annual grassland in the State California (54% - 59%) [40] and for the Montane grasslands of South Africa (40% - 76%) [41]. The estimates for evapotranspiration for different regions of the world vary between 59.4% and 90% [42]-[49]. Less evapotranspiration from the Sundarban mangrove sur-

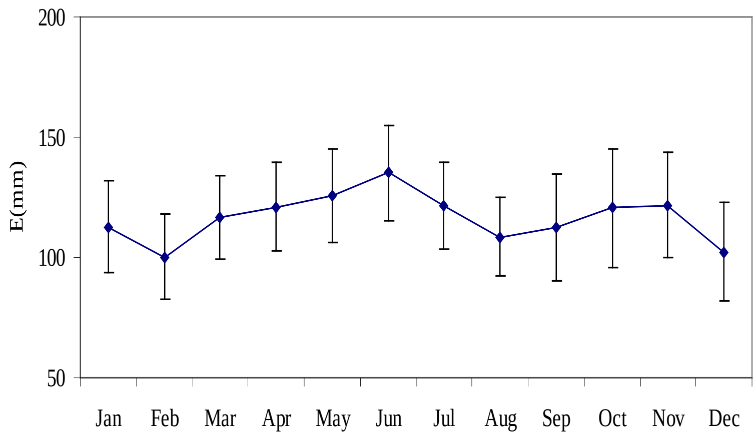


Figure 2. Monthly mean evapotranspiration at Sundarban mangrove forest.

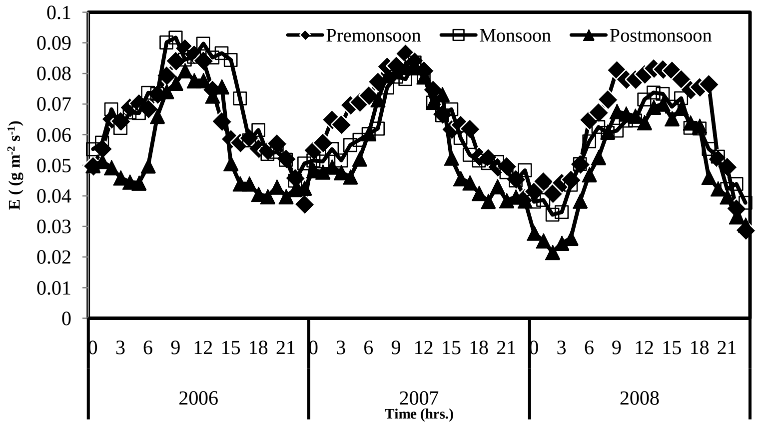


Figure 3. Diurnal variation of evapotranspiration (E) in three different seasons during the study period (2006-2008) at Sundarban mangrove ecosystem.

face was reported during winter (north east monsoon) when cool and dry wind (with relatively lower wind velocity, temperature and humidity compared to monsoon and pre-monsoon) blows over the forest canopy irrigated with warm tidal water.

Diurnal pattern of evaporation rate during three different seasons at Sundarban mangrove ecosystem (**Figure 3**) showed daytime maximum with about 52% reduction during nighttime. Daley *et al.* [50] obtained 50% decrease of transpiration rate relative to that of daytime for paper Brich forest. Nighttime transpiration rates (Enight) varied from 5% to 15% of daytime rates with a maximum of 30% for irrigated *Eucalyptus grandis* plantation [51]-[54].

Evaporation is controlled both by the amount of available energy and plant physiological activity (*i.e.* stomata opening and closing). Transpiration is insignificant at night when stomata remain closed. However, stomata of some species could remain open at night, for nighttime transpiration driven by environmental forcing.

3.6. Vapour Pressure Deficit

Vapour pressure deficit (VPD) is one of the major criteria of plant growth. As a general rule, most plants grow well at VPD values of between 0.8 to 0.95 kPa [55]. In the Sundarban Mangrove forest mean annual distribution of VPD curve followed the trend of water availability and diurnal solar radiation all over the year. In the daytime VPD was regulated by atmospheric temperature. VPD values ranged from 0.093 to 2.17 kPa all over the year in this ecosystem with a maximum during post-monsoon season (**Figure 4**). In spite of lower temperature intrusion of dry northeast monsoonal wind from the landward direction to the mangrove environment could be the reason behind the higher values of VPD during the post-monsoon period.

3.7. Canopy Resistance

The canopy resistance r_c, is the resistance of all stomata of the leaves and depend primarily on solar radiation, vapour pressure deficit and soil moisture deficit. Canopy resistance (r_c) is one of the important factors controlling biosphere-atmosphere exchange of water vapour [56]-[58] apart from r_a (aerodynamic resistance) and r_s (surface layer resistance). A typical steady increase in the forest canopy resistance during daytime hours was observed (**Figure 5**). Annual daytime and nighttime mean of canopy resistance was found to be 1.78 and 0.68 $s \cdot cm^{-1}$ respectively in this mangrove forest. The highest value was obtained during the daytime (3.4 $s \cdot cm^{-1}$) in the pre-monsoon whereas the lowest value was recorded 0.045 $s \cdot cm^{-1}$ at night in the monsoon period. During the monsoon, the r_c values were recorded lower both in the day and night time compared to that of pre-monsoon and post-monsoon. The low value of canopy resistance in the morning (1 - 2 $s \cdot cm^{-1}$) and its steady increase during the (4 $s \cdot cm^{-1}$) daytime from Douglas-fir forest was also observed by McNaughton and Black [57]. Similar daytime courses of canopy resistance have been reported by Stewart and Thorn [56] and Gash and Stewart [58] for a pine forest with high values of soil water potential. A significant negative correlation was found between canopy resistance and relative humidity (**Figure 6**).

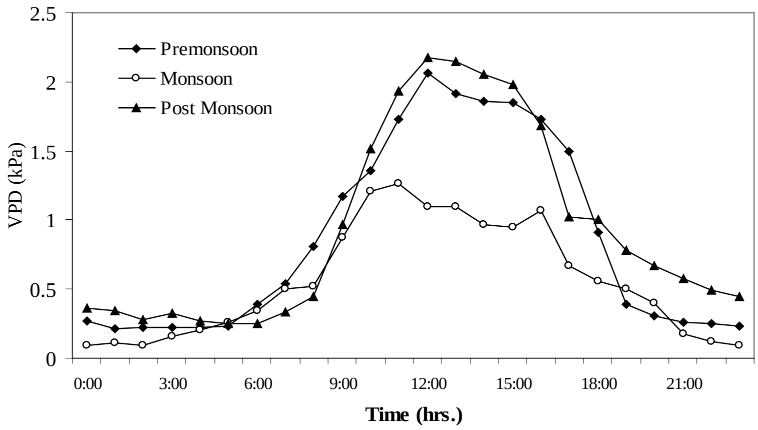


Figure 4. Diurnal variation of VPD in three different seasons at Sundarban mangrove ecosystem.

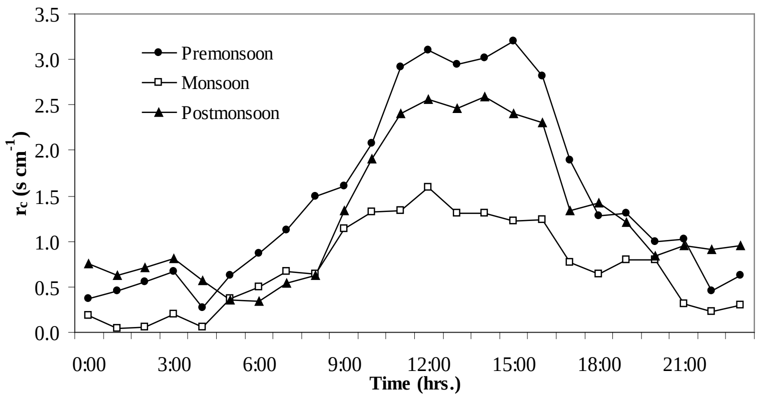


Figure 5. Diurnal variation of canopy resistance in three different seasons at Sundarban mangrove ecosystem.

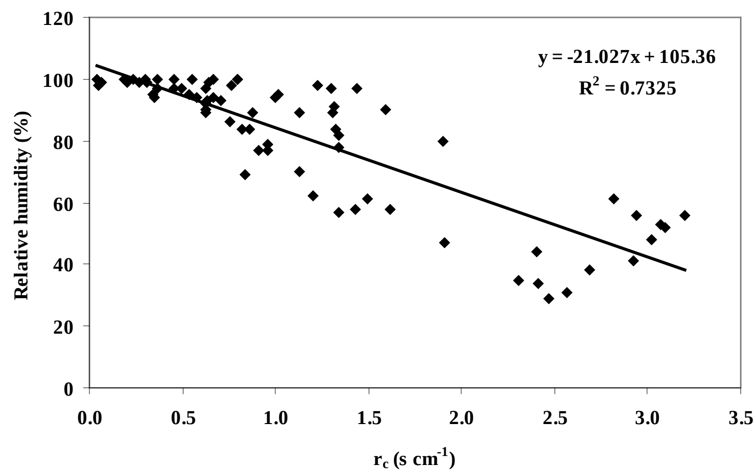


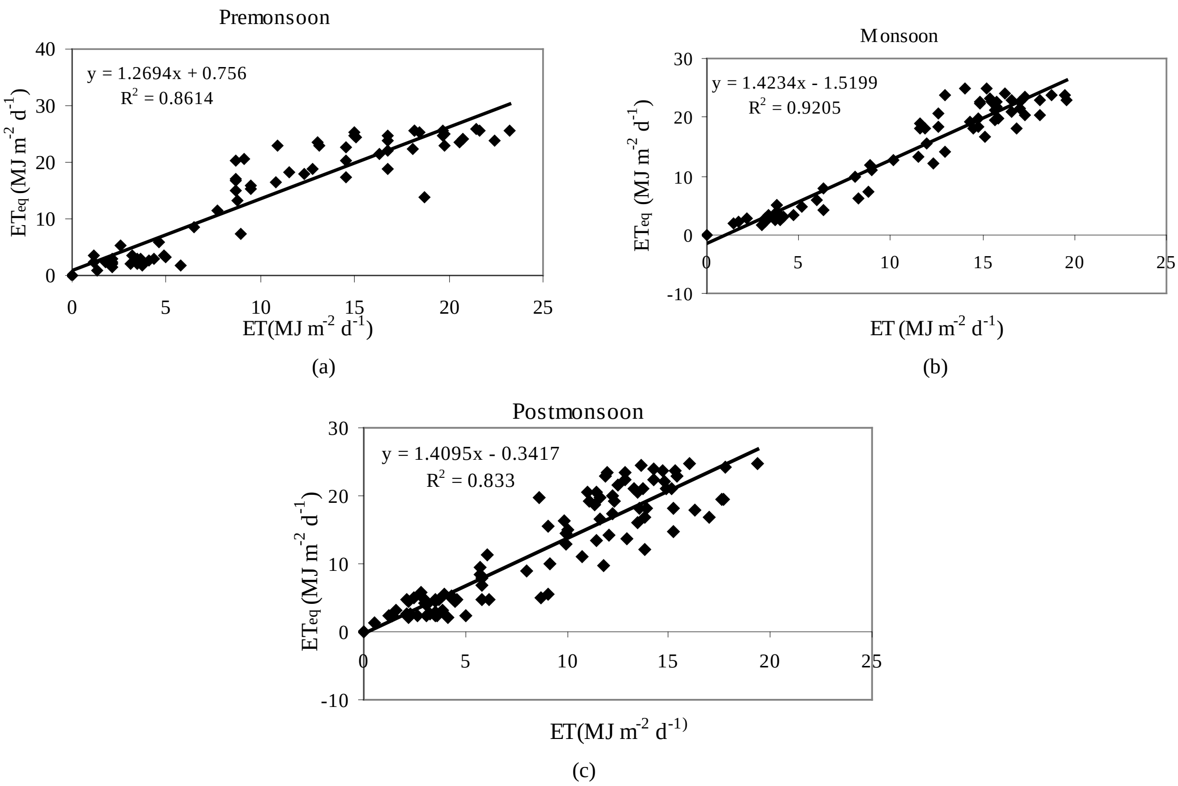
Figure 6. Correlation between canopy resistance and relative humidity at Sundarban mangrove ecosystem.

Figures 7(a)-(c) depict the correlation between ETeq and measured ET and significant correlations in all the seasons were obtained. The relative transpiration rate (ET/ETeq) (*i.e.* actual to equilibrium) varied between 0.92 ± 0.32, 0.79 ± 0.33 with a maximum value during monsoon and Price and Woo [59] Thompson *et al.* [60] suggested that a canopy could have a greater transpiration rate in wet condition than that of a dry condition.

The ratio ET/ETeq known as Priestley-Taylor parameter exhibited a negative relation with canopy resistance (**Figure 8**), indicating greater canopy resistance while there was limited water availability at low ET/ETeq.

4. Conclusion

This study reports on temporal variation of water vapour mixing ratio in the atmosphere and its exchange rate in the Sundarbans mangrove biosphere. The magnitude and dynamics of evapotranspiration (ET) exhibited seasonality dominated by monsoon and annually 67.7% of total precipitation was consumed by evapotranspiration. During the wet season (monsoon), the mean evapotranspiration rate was 0.055 ± 0.015 $g \cdot m^{-2} \cdot s^{-1}$ and was 12% -



(a) (b) (c)

Figure 7. The correlation between ET and ETeq in (a) pre-monsoon; (b) monsoon; (c) post-monsoon, at Sundarban mangrove ecosystem.

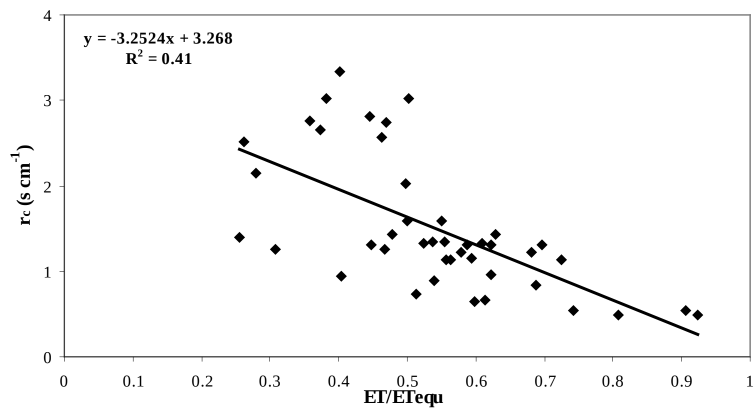


Figure 8. Correlation between ET/ETeq and canopy resistance of mangrove forest, at Sundarban.

25% higher than during the dry season (pre- and post-monsoon). There seems to be significant impact of the monsoonal period on canopy resistance. Evapotranspiration in the mangrove forest seems to be controlled by the monsoonal cycle in association with plant physiological activity (*i.e.* stomata opening and closing).

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References

[1] Pallardy, S.G. (2007) Physiology of Woody Plants. Academic Press, Waltham.

[2] Baumgartner, A. and Reichel, E. (1975) World Water Balance: Mean Annual Global, Continental and Maritime Precipitation, Evaporation and Run-Off. Elsevier, Amsterdam.

[3] Kurc, S.A. and Small, E.E. (2004) Dynamics of Evapotranspiration in Semiarid Grassland and Shrubland Ecosystems during the Summer Monsoon Season, Central New Mexico. *Water Resources Research*, **40**, Article ID: W09305. http://dx.doi.org/10.1029/2004WR003068

[4] Decker, J.P., Gaylor, W.G. and Cole, F.D. (1962) Measuring Transpiration of Undisturbed Tamarisk Shrubs. *Plant Physiology*, **37**, 393-397. http://dx.doi.org/10.1104/pp.37.3.393

[5] Priestley, C.H.B. and Taylor, R.J. (1972) On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters. *Monthly Weather Review*, **100**, 81-92. http://dx.doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2

[6] Law, B.E., Falge, E. and Gu, L. (2002) Environmental Controls over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation. *Agricultural and Forest Meteorology*, **113**, 97-120. http://dx.doi.org/10.1016/S0168-1923(02)00104-1

[7] Kellomaki, S. and Wang, K. (1999) Short-Term Environmental Controls of Heat and Water Vapor Fluxes above a Boreal Coniferous Forest: Model Computations Compared with Measurements by Eddy Correlation. *Ecological Modelling*, **24**, 145-173. http://dx.doi.org/10.1016/S0304-3800(99)00159-3

[8] Barford, C.C., Wofsy, S.C. and Goulden, M.L. (2001) Factors Controlling Long- and Short-Term Sequestration of Atmospheric CO_2 in a Mid-Latitude Forest. *Science*, **294**, 1688-1691. http://dx.doi.org/10.1126/science.1062962

[9] McKinley, G.A., Follows, M.J. and Marshall, J. (2004) Mechanisms of Air-Sea CO_2 Flux Variability in the Equatorial Pacific and the North Atlantic. *Global Biogeochemical Cycles*, **18**, 2011-2025. http://dx.doi.org/10.1029/2003GB002179

[10] Malhi, Y. and Wright, J. (2004) Spatial Patterns and Recent Trends in the Climate of Tropical Rainforest Regions. *Philosophical Transactions of Royal Society London Series B*, **359**, 311-329. http://dx.doi.org/10.1098/rstb.2003.1433

[11] Bousquet, P., Peylin, P., Ciais, P., Le Quere, C. and Friedlingstein, P.P. (2000) Tans, Regionial Changes in Carbondioxide Fluxes of Land and Oceans since 1980. *Science*, **290**, 1342-1346. http://dx.doi.org/10.1126/science.290.5495.1342

[12] da Rocha, H.P., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., de Freitas, H.C. and Silva Figueira, A.M.E. (2004) Seasonality of Water and Heat Fluxes over a Tropical Forest in Eastern Ammazonia. *Ecological Applications*, **14**, 822-832. http://dx.doi.org/10.1890/02-6001

[13] Malhi, Y., Pegoraro, F., Nobre, A.D., Pereira, M.G.P., Grace, J., Culf, A.D. and Clement, R. (2002) Energy and Water Dynamics of a Central Amazonian Rain Forest. *Journal of Geophysical Research*, **107**. http://dx.doi.org/10.1029/2001JD000623

[14] Shuttleworth, W.J., Sash, H.C., Lloyd, C.R., Moore, C.J., Roberts, J., Marques Filho, A.D.O., Fisch, G., Silva Fillro, V.D.P., Nobre, I.C.A., Cabral, O.M.R., Paiel, S.R. and Moraes, J.C. (1984) Eddy Correlation Measurements of Energy Partition for Amazonia Forest. *Quarterly Journal of the Royal Meteorological Society*, **110**, 1143-1163. http://dx.doi.org/10.1002/qj.49711046622

[15] Gupta, S.K. and Deshpande, R.D. (2004) Water for India in 2050: First Order Assessment of Available Options. *Current Science*, **86**, 1216-1224.

[16] Kumar, R., Singh, R.D. and Sharma, K.D. (2005) Water Resources of India. *Current Science*, **89**, 794-811.

[17] Garg, N.K. and Hassan, Q. (2007) Alarming Scarcity of Water in India. *Current Science*, **93**, 932-941.

[18] Planning Commisson (2007) Report of the Expert Group on Ground Water Management and Ownership. Government of India, New Delhi.

[19] Narasimhan, T.N. (2008) A Note of India's Water Budget and Evapotranspiration. *Journal of Earth System Science*, **117**, 237-240. http://dx.doi.org/10.1007/s12040-008-0028-8

[20] Jain, S.K., Agarwal, P.K. and Singh, V.P. (2007) Hydrology and Water Resources of India. Springer, Dordrecht, 1258.

[21] National Circumstances (2004) India's Initial National Communication to the United Nations Framework Convention on Climate Change, Chapter-1. 3-28. http://unfccc.int/resource/docs/natc/indnc1.pdf

[22] Hutley, L.B., Grady, A.P.O. and Eamus, D. (2001) Monsoonal Influence on Evapotranspiration of Savanna Vegetation of Northern Australia. *Oecologia*, **26**, 434-443. http://dx.doi.org/10.1007/s004420000539

[23] Clough, B. (1998) Mangrove Forest Productivity and Biomass Accumulation in Hinchinbrook Channel, Australia. *Mangroves and Salt Marshes*, **2**, 191-198. http://dx.doi.org/10.1023/A:1009979610871

[24] Chakrabarty, K. (1987) Sundarban Mangrove in India—A Study of Conservation Status. *Indian Forest*, **113**, 352-358.

[25] Gopal, B. and Chauhan, M. (2006) Biodiversity and Its Conservation in the Sundarban Mangrove Ecosystem. *Aquatic Sciences*, **68**, 338-354. http://dx.doi.org/10.1007/s00027-006-0868-8

[26] Alongi, D.M. and Robertson, A.I. (1995) Factors Regulating Benthic Food Chains in Tropical River Deltas and Adjacent Shelf Areas. *Geo-Marine Letters*, **15**, 145-152. http://dx.doi.org/10.1007/BF01204456

[27] Millero, F.J. (1996) Chemical Oceanography. 2nd Edition, CRC Press, New York.

[28] Arya, S.P. (2001) Introduction to Micrometeorology. Academic Press, New York.

[29] Tan, C.S. and Black, T.A. (1976) Factors Affecting the Canopy Resistance of a Douglas-Fir Forest. BLM, 475-488.

[30] Priestley, C.H.B. (1959) Turbulent Transfer in the Lower Atmosphere. University of Chicago Press, Chicago.

[31] Wesely, M.L. and Hicks, B.B. (1977) Some Factors That Affect the Deposition Rates of Sulfur Dioxide and Similar Gases on Vegetation. *Journal of the Air Pollution Control Association*, **27**, 1110-1116. http://dx.doi.org/10.1080/00022470.1977.10470534

[32] Bodek, I., Lyman, W.J., Reehl, W.F. and Rosenblatt, D.H. (1988) Environmental Inorganic Chemistry. Pergamon Press, Oxford.

[33] Allen, G.R., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop Evapotranspiration, Food and Agriculture Organization (FAO) of the United Nations, 8.

[34] Ward, A.D., Trimble, S.W. and Wolman, M.G. (2004) Environmental Hydrology. 2nd Edition, Lewis Publishers, Boca Raton, Florida.

[35] Barr, D., Barr, J.G., Fuentes, J.D., Zieman, J.C., Grahl, T. and Childars, D. (2005) Seasonal Controls on Energy Partitioning Patterns of a Mangrove Forest, FCE LTER. *All Scientists Meeting*, 25-26 March 2005.

[36] Ganguly, D., Dey, M., Mandal, S.K., De, T.K. and Jana, T.K. (2008) Energy Dynamics and Its Implication to Biosphere-Atmosphere Exchange of CO_2, H_2O and CH_4 in a Tropical Mangrove Forest Canopy. *Atmospheric Environment*, **42**, 4172-4184. http://dx.doi.org/10.1016/j.atmosenv.2008.01.022

[37] Miyazaki, S., Yasunari, T., Miyamoto, T., Kaihotsu, I., Davaa, G., Oyunbaatar, D., Natsagdorj, L. and Oki, T. (2004) Agrometeorological Conditions of Grassland Vegetation in Central Mongolia and Their Impact for Leaf Area Growth. *Journal of Geophysical Research*: *Atmospheres*, **109**, Published Online. http://dx.doi.org/10.1029/2004JD005179

[38] Zhang, Y., Munkhtsetseg, E., Kadota, T. and Ohata, T. (2005) An Observational Study of Ecohydrology of a Sparse Grassland at the Edge of the Eurasian Cryosphere in Mongolia. *Journal of Geophysical Research*: *Atmospheres*, **110**, Published Online. http://dx.doi.org/10.1029/2004JD005474

[39] Li, S.G., Asanuma, J., Kotani, A., Davaa, G. and Oyunbaatar, D. (2007) Evapotranspiration from a Mongolian Steppe under Grazing and Its Environmental Constraints. *Journal of Hydrology*, **333**, 133-143. http://dx.doi.org/10.1016/j.jhydrol.2006.07.021

[40] Baldocchi, D.D., Xu, L. and Kiang, N. (2004) How Plant Functional-Type, Weather, Seasonal Drought and Soil Physical Properties Alter Water and Energy Fluxes of an Oak-Grass Savanna and an Annual Grassland. *Agricultural and Forest Meteorology*, **123**, 13-39. http://dx.doi.org/10.1016/j.agrformet.2003.11.006

[41] Everson, C.S. (2001) The Water Balance of a First Order Catchment in the Montane Grasslands of South Africa. *Journal of Hydrology*, **241**, 110-123.

[42] Shiklomanov, I.A. (1997) Comprehensive Assessment of the Freshwater Resources of the World. World Meteorological Organization, Stockholm, 88.

[43] Australian Water Resources (2005) Water Availibility, Australian Water Resources. http://www.water.gov.au/WaterAvailability/

[44] Marengo, J.A. (2006) On the Hydrological Cycle of the Amazonbasin: A Historical Review and Current State-of-the-Art. *Revista Brasileira de Meteorologia*, **21**, 1-19.

[45] Berbery, E.H. and Barros, V.R. (2002) The Hydrological Cycle of the La Plata Basin in South America. *Journal of*

Hydrometeorology, **3**, 630-645. http://dx.doi.org/10.1175/1525-7541(2002)003<0630:THCOTL>2.0.CO;2

[46] Institut Francais de L'Environment (2004) L'e/tat des eaux souterraines en France, aspects quentitatifs et qualitatifs. Report, Institut francais de l'environment, Orle/ans, Etudes et Travaux n043, 34.

[47] Department of Water Resources, State California (2005) Water Plan Update 2005, Public Review Draft, Vol. 3.

[48] Loescher, H.W., Gholz, H.L., Jacobs, J.M. and Oberbauer, S.F. (2005) Energy Dynamics and Modeled Evapotranspiration from a Wet Tropical Forest in Costa Rica. *Journal of Hydrology*, **315**, 274-294.

[49] Leopold, L.B. (1974) Water: A Primar. W. H. Freeman, San Francisco, 172.

[50] Daley, M.J. and Phillips, N.G. (2006) Interspecific Variation in Nighttime Transpiration and Stomatal Conductance in a Mixed New England Deciduous Forest. *Tree Physiology*, **26**, 411-419. http://dx.doi.org/10.1093/treephys/26.4.411

[51] Benyon, R. (1999) Nighttime Water Use in an Irrigated *Eucalyptus grandis* Plantation. *Tree Physiology*, **19**, 853-859. http://dx.doi.org/10.1093/treephys/19.13.853

[52] Snyder, K.A., Richards, J.H. and Donovan, L.A. (2003) Night-Time Conductance in C3 and C4 Species: Do Plants Lose Water at Night? *Journal of Experimental Botany*, **54**, 861-865.

[53] Bucci, S.J., Scholz, F.G., Goldstein, G., Meinzer, F.C., Hinojosa, J.A., Hoffman, W.A. and Franco, A.C. (2004) Processes Preventing Nocturnal Equilibration between Leaf and Soil Water Potential in Tropical Savanna Woody Species. *Tree Physiology*, **24**, 1119-1127. http://dx.doi.org/10.1093/treephys/24.10.1119

[54] Scholz, F.G., Bucci, S.J., Goldstein, G., Meinzer, F.C., Franco, A.C. and Miralles-Wilhelm, F. (2007) Removal of Nutrient Limitations by Long-Term Fertilization Decreases Nocturnal Water Loss in Savanna Trees. *Tree Physiology*, **27**, 551-559. http://dx.doi.org/10.1093/treephys/27.4.551

[55] Autogrow Systems Ltd. Web Site, Humidity Page.

[56] Stewart, J.B. and Thorn, A.S. (1973) Energy Budgets in a Pine Forest. *Quarterly Journal of the Royal Meteorological Society*, **99**, 154-170. http://dx.doi.org/10.1002/qj.49709941913

[57] McNaughton, K.G. and Black, T.A. (1973) A Study of Evapotranspiration from a Douglas-Fir Forest Using the Energy Balance Approach. *Water Resources Research*, **9**, 1579-1590. http://dx.doi.org/10.1029/WR009i006p01579

[58] Gash, J.H.C. and Stewart, J.B. (1975) The Average Surface Resistance of a Pine Forest Derived from Bowen-Ratio Measurements. *BLM*, **8**, 453-464.

[59] Price, J.S. and Woo, M.K. (1988) Studies of a Subarctic Coastal Marsh. *Journal of Hydrology*, **103**, 275-292.

[60] Thompson, M.A., Campbell, D.I. and Spronken-Smith, R.A. (1999) Evaporation from Natural and Modified Raised Peat Bogs in New Zealand. *Agricultural and Forest Meteorology*, **95**, 85-98. http://dx.doi.org/10.1016/S0168-1923(99)00027-1