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Research Article

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Seasonal changes of energy fluxes of a subtropical mangrove forest in Zhangjiang Estuary, China

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ABSTRACT

Energy flux and regulating factors were examined over an entire year (2010) in mangrove wetland in Zhangjiang estuary. The results show that the seasonal changes of the energy fluxes and Bowen ratio (β) were greatly affected by net radiation. The opposite seasonal dominant of the LE and H_s resulted in significant seasonal changes in Bowen ratio (β).During winter season, β could reach a maximum of 1.52.While enter summer days, β fluctuated from 0.37 to 1.0. Tidal activity had different effects on energy budget in different seasons. During tidal flooding days, β was slightly lower than that at exposure days in the winter, while β was significantly reduced in the summer. In addition, the energy balance ratio (EBR) was reduced significantly during flooding days in winter, while summer is just the opposite, a higher EBR was obtained. However, the ecosystem energy balance is impacted by the tide is very complex, thus more research are needed in future.

Key words: Mangrove, Bowen ratio, Tidal activity, Energy budget, Energy balance ratio

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INTRODUCTION

Energy exchange between the land surface and the atmosphere is one of the most important processes in ecosystems because it affects many ecosystem processes such as water transport, plant growth and many other ecosystems processes [1]. Thus energy fluxes (latent and sensible heat fluxes) are important variables in meteorological, hydrological and ecological analyses. So it is necessary to understand the magnitude and changes of energy fluxes as well as the regulatory mechanisms, which is help to better understand the regional and global scalec limatological processes.

Generally, evapotranspiration consumed largest part of available energy during growing season in vegetated wetlands[2-5]. The land-ocean boundary of wetland is inundated by the lunar tide. Besides of vertical energy fluxes, tidal water acts as an advectional energy source or sink, plays an important role in regulating energy partitioning and the energy balance deficit in coastal ecosystems [5-10]. For example: Guo *et al.*[5] observed β was slightly higher than that at exposure days in most cases during tidal flooding days in estuarine wetland located in Dongtan of Chongming Island, northeast of Shanghai. However, little has been studied on energy fluxes and energy balance in mangrove wetlands.

The Zhangjing estuary mangrove forest is an inter-charge of fresh water from upstream of Zhangjiang River and sea water from the downstream of the East China Sea. Height of dominant mangrove plants genera such as *Kandel. Obovata* Sheue, Liu et Yong, *Aegiceras corniculatum*(L.) Blancoand *Avicinia.marina* (Forsk.) Vierh is lower than 7 m. The climate of the area is sub-tropical marine monsoon climate. The mean annual precipitation and air temperature were 1714.5 mm and 21.2^{o}C, respectively. Tide was semidiurnal with maximum amplitude of about 2 m. Salinity of the tidal water varied between 2 ppt and 26 ppt.

The primary focus of this paper is to 1) examine and describe the magnitude of seasonal variations in the energy flux and partitioning pattern; 2) explore the regulation of environmental factors on energy flux; and 3) quantify the effect of tidal flooding on energy partitioning in the subtropical mangrove forest in Zhangjiang estuary.

EXPERIMENTAL SECTION

Materials and Methods

Sampling location

The Zhangjiang estuary mangrove forest (23^o 55'N, 117^o 23'E) is located within the Zhangjiangkou National Mangrove Nature Reserve in Yun Xiao county in Fujian province, and covers a core area of about 65 km^2. And this site is far from the Dongshan Bay with a long distance of 5.5 km, thus creating the long mud flat, and the mangrove mud flat is a gradual zonation. In August of 2008, we established one eddy covariance (EC) tower in the middle of site to perform micrometeorological surveys.

Field measurement

Sensible heat (H_s) and latent heat (LE) fluxes were quantified at 7 m using the eddy-covariance technique. The system consists of a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific Inc. (CSI), Logan, UT, USA), which measures wind speed and sonic temperature, and an open-path CO_2/H_2O infrared gas analyzer (IRGA, Li-7500, Li-Cor Inc., Lincoln (Li-Cor), NE, USA). The observations it has a sufficiently wide fetch of at least 300–500 m in all directions. The CO_2/H_2O sensor head was installed downwind of the sonic anemometer in the predominant wind direction, and the analyzer was calibrated every six months. Both CSAT-3 and Li-7500 were operated at a frequency of 10 Hz. The data were stored in a built-in data logger (CR3000, CSI).

Meteorological data was measured at 30-min intervals including temperature and relative humidity (HMP45C, Vaisala, Finland) at two heights, net radiation (CNR1, Kipp and Zonen, Delft, Holland), photosynthetically active radiation (LI-190SB, Li-COR, Inc), and precipitation (TE525, Texas Electronics, Texas, USA),all of whose sensors were mounted on the tower. Soil temperature (CS107, CSI) and soil heat flux (HFT-3, CSI) were also measured at a depth of 5 cm, 10 cm and 20 cm. All of the above variables were automatically stored in the CR3000 data logger at half-hourly intervals. Additionally, tidal water was monitored by a water gauge (Sonde, model 600LS, YSI, USA) which recorded the temperature, depth and salinity of the tidal water at 10-minute intervals, then transformed them to 30-minute intervals.

Data processing

Prior to calculating the fluxes of sensible and latent heat, the high-frequency data need to be processed, including spike removal, the correction of the two-dimension coordinate rotation to adjust the x-axis to be parallel with the local main wind direction, WPL density correction[11]. Data from stable nocturnal periods were also excluded, specifically when the friction velocity(μ*) was <0.1 m s^{-1}.The influence of water vapor on the sonic temperature measurement [12], and the effect of air density fluctuation on CO_2 and heat fluxes [11] were corrected in sequence. In addition, the corrected dataset was further filtered with weather condition (rain event), and instrument malfunctions or power failure. Stationary test was applied with a threshold of 30% [13]. Overall, approximately 88% of the 30-min data of H_s and LE were retained.

Biophysical modeling

The energy balance closure was evaluated for each site using two different averaging periods (half-hourly and daily), with linear regressions used for each case, of dependent flux variables (LE+H_s) against the independently derived energy(R_n-G-G_s). The energy balance ratio (EBR) was calculated using the following equation [5]:

$$EBR= (H_s+LE)/(R_n–G–G_s)$$

where R_n is net radiation, G is soil heat flux, Hs is sensible heat, LE is latent heat, and G_s is the advected heat from tidal tide which was not included in EBR calculation in this study due to different estimation. Considering the relatively short vegetation (< 8 m) in our areas, the canopy storage energy is negligible.

Daytime Bowen ratio (β)was calculated to describe the partitioning of the energy component, using the following equation:

$$\beta=Hs/LE$$

Data between 11:00 and 16:00 were used to calculate daily Bowen ration in this study.

RESULTS AND DISSCUSION

Meteorological conditions

Distinct seasonal changes of air temperature (T_a) and vapor pressure deficit (VPD) were observed. The highest mean daily temperature and PAR were recorded in August, while the lowest were recorded in February (Fig. 1a). The highest mean daily VPD also were recorded in August, but the lowest were recorded in January (Fig. 1b). The seasonal change of the incoming shortwave radiation was relatively small (Fig. 1a).Total precipitation record was 1102.7 mm year-round. Generally, the mean daily water level was close to 40 cm for its higher elevations. And the change of tidal water salinity was dramatic with the range of 1.5-20.9 ppt.

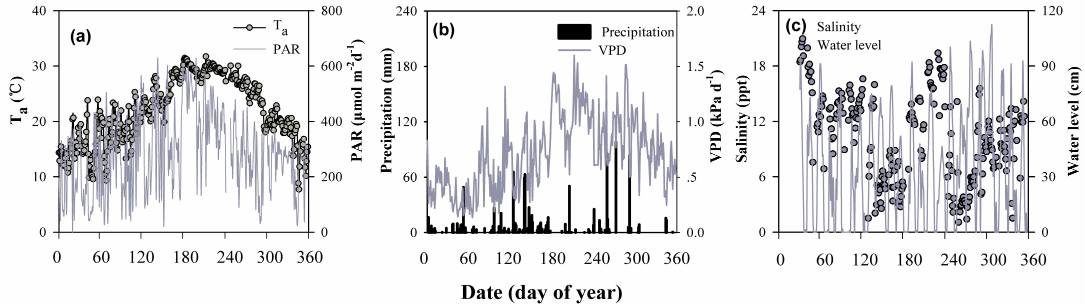

Fig.1 Seasonal changes of meteorological variables daily mean (a) air temperature (T_a)and photosynthetically active radiation (PAR), (b) daily sum of rainfall and daily mean vapor pressure deficit (VPD) and (c) daily mean salinity and water level from Jan 2010 to Dec 2010 *(For salinity and water depth, data from January to February were lack).*

Energy balance closure

The degree of the energy balance closure was examined by regressing the latent plus sensible heat flux (LE+H_s) and the available energy, the net radiation minus ground heat flux (R_n-G)(Table 1). The slope of this relationship, when considering all of the half-hour data collected over the entire year was 0.7091. The intercept of this same relationship was 23.8922Wm^{-2}and the coefficient of determination (R^2) was 0.9894. The average slope values increased to 0.7942 when using the daily sum data instead of the half-hour value to calculate the regression coefficients of LE+H_s against R_n-G (Table 1). In addition, the seasonal energy balance ratio (EBR) was also calculated. The mean annual EBR for our site was 0.8416.

Table 1Whole-year energy balance closure statistics using half-hourly and daily sum data values

	Half-hour value	Daily sum value
Slope	0.7091	0.7942
Intercept	23.8922	0.4566
R^2	0.9894	0.8739

The degree of energy balance closure is usually used to evaluate the performance of the eddy-covariance system and long-termeddy-covariance studies had revealed that a frequent occurrence of this lack of energy balance closure was common [14-16]. The degree of closure of daily sum data of our site was as high as the reported values in FLUXNET(0.79±0.01)[14] and the energy balance ratio was a little higher than China FLUX synthesis (0.83) [16], suggesting adequate performance of the eddy-covariance system. But the degree of closure of half-hour data was much lower than that of daily sum data. The imbalances of energy budget have been observed in almost every EC system, and possible explanation was summarized in Wilson et al.[14].Additionally, tidal water acts as an advectional energy source or sink in coastal wetland, would also account for this imbalance in our study area. If this part of advectional heat exchange between tidal water and ecosystem can be quantified, the energy budget ratio would be greatly improved by calculated according to the report of Burba et al.[17], 20%–30% of R_n could be consumed by 0.5 m deep water body and became a great heat sink in the day time and would be released into a huge energy source in night.

Seasonal energy flux partitioning

The seasonal pattern of energy fluxes of R_n among LE, H_s and soil heat flux (G) was shown in Fig. 2.Net radiation (R_n) exhibited a clear seasonal dynamic (Fig.2a), fluctuating in concert with PAR (Fig. 2a).The annual variation of LE showed the similar one-peak curve with the change of R_n, while LE was relatively low in winter and early spring, then started to rapidly increase after April. The maximum value of LE appeared in July, and LE dominated in summer. H_s and LE shifted, and dominated in different seasons. Therefore the seasonal pattern of H_s was different with that of LE. H_s increased with the increasing of R_n in winter days, and dominated in winter. However, H_s always kept lower value in summer even though R_n kept increasing. Compared with H_s, LE shows a slightly higher dependency on R_n. The soil heat flux shows little variation through seasons with low magnitudes.

Diurnal variation of energy fluxes (both LE and H_s) changed with R_n all year round (Fig. 3). In winter season, R_n reached as high as 485.54 W/m^2, and LE and H_s peaked at 110.22 $W/m^2$and 204.54 W/m^2, respectively. In summer season, R_n increased to 660.55 W/m^2, and LE showed a dramatic increase up to 297.08 W/m^2, but H_s only reached maximum at 180.08 W/m^2. Both LE and H_s peaked half-hour to two hours after R_n reached maximum. G was so few diurnal variation through of G was not obvious.

The seasonal changes of LE flux (i.e. evapotranspiration) are often affected by the seasonal changes in the air as well as soil temperatures, radiation, VPD, precipitation and LAI[18, 19]. In our study, temperature and radiation increases, coupling with vegetation development were the primary reasons for LE increase during the summer period. However, LE was lower than H_s during winter season. The phenomenon was much different from previous researches in the wet tropical forest [20], where latent heat flux was always greater than sensible heat. We attributed the difference between mangrove and wet tropical forest to the hydraulic or salinity stress condition caused by tidal activity during winter, which caused evapotranspiration rates suppressed. Our result is consistent with Barr et al.[8] shows that the mangrove ecosystem is extremely water conservative.

Bowen ratio (β, H_s/LE)can reflect changes in energy partitioning. Corresponding to the shifting dominance between LE and Hs, rapid and extreme seasonal changes in the Bowen ratio (β, H/LE) were also observed at our site(Fig.2b), showed a "U" shape, fluctuating in contrast with the net radiation. During the winter and spring, lower surface and air temperatures and net radiation resulted in suppressed surface evaporation, β was above unity, even rise to a maximum of 1.52 in January. Then β declined into the summer during the onset of the wet season. LE, driven primarily by surface evaporation, consumed a greater proportion of the available energy. Hence β was always below unity, even reaching as low as 0.37. Thus, regional irradiance and temperature trends, as opposed to plant physiological controls, governed the observed seasonal trend in Bowen ratios.

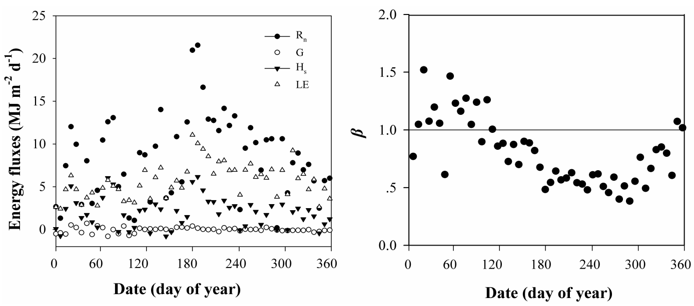

Fig. 2 Seasonal patterns of (a) energy fluxes from including net radiation (R_n), latent heat (LE), sensible heat (H_s) and soil heat flux (G). The seasonal patterns of daily average of midday mean (b) Bowen ratio from Jan 2010 to Dec 2010

Midday means the time course from 10:00 am to 16:00 pm local standard time.

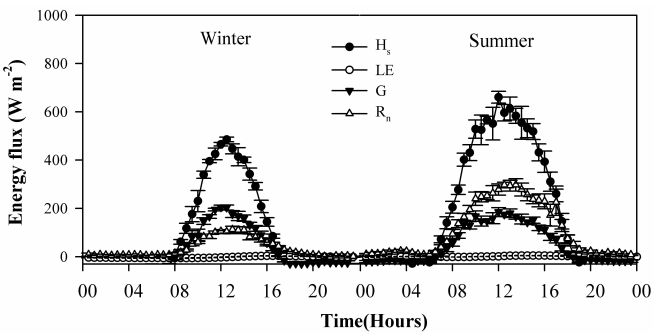

Fig. 3 Several days ensemble averages of diurnal energy fluxes in (a) winter and (b) summer season

Tidal activity on energy partitioning

In different seasons, tidal water may be acting as a source of or sink for energy, releasing heat to the ecosystem or absorb heat form ecosystem, and influence the energy closure and distribution of mangrove ecosystem. During winter season, average β reached 1.66±0.05 during exposed days, while declined to 1.23 during flooding days. That was to say, more energy was partitioned as latent heat during flooding days than exposed days. However, summer was just the opposite, average β increased significantly during flooding days (p<0.05), in other words, more energy existed as sensible heat during flooding days in summer(Fig.4a).In addition, tidal activity had different effects on energy budget ratio in different seasons. Energy budget ratio of mangrove ecosystem was reduced significantly during flooding days in winter, while summer was just the opposite, to a certain extent, the higher energy budget ratio was obtained (Fig.4b).

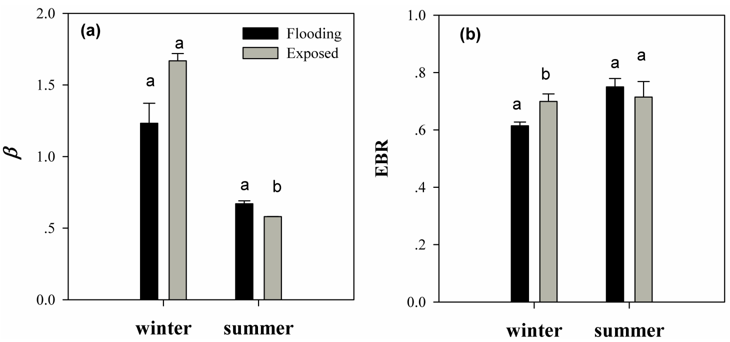

Fig. 4 Tidal influence on (a) energy partitioning and (b) energy budget-EBR of mangrove ecosystem in winter and summer

To further analyze the mechanism of tidal activity on energy partitioning in mangrove ecosystem, several sunny days including tidal and non-tidal activity in the winter and summer were choose. At the same time, climatic factors (air temperature, water temperature and so on) were also analyzed. Generally, available energy was mainly partitioned to H_s without tidal activity in winter. While H_s reduced or LE increased during flooding days (Fig.5a). That's because water temperature was lower than air temperature in winter (Fig.5e). Colder water cooled the air, and thereby resulted in the decrease of H_s (Fig.5c). In addition, a great of vapor brought with tidal water evaporation, might increase LE to some extent. Thus, Bowen ratio was reduced during flooding days in winter. On the contrary, during summer season, water temperature was higher than air temperature (Fig.5f). Warmer water warmed the air, and thus increased H_s (Fig.5d). Moreover, the high water vapor density or low vapor pressure deficit during flooding days depressed the evaporation or transpiration. The stress under water flooding may also suppress transpiration activity [21, 22]. Thus, Bowen ratio increased during flooding days in summer. However, different mechanisms may exist for tidal effect on energy partitioning, which requires further work.

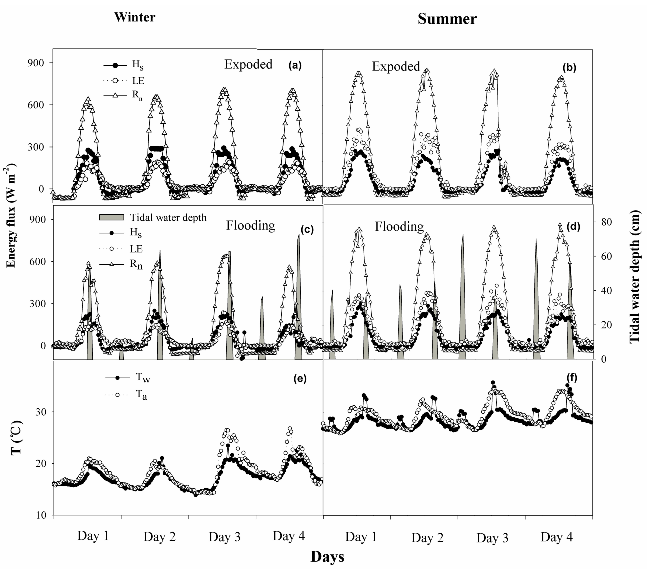

Fig.5 Tidal influence on energy flux in different seasons
(H_s : sensible heat, LE: latent heat, R_n: net radiation, T_w: water temperature, T_a: air temperature)

CONCLUSION

The energy budget and regulating factors were investigated over a subtropical mangrove forest in Zhangjiang estuary during one year of continuous measurement in 2010. Like observed in other vegetated wetlands, latent heat was the largest consumer of incoming energy during summer season. In comparison, more energy was dissipated as sensible heat during winter season. Besides net radiation, hydraulic or salinity stress during dry season, were another most important factors resulting latent heat flux equal to or lower than H_s, and the mangrove ecosystem is extremely water conservative. Net radiation also drove the diurnal pattern of energy fluxes.

Tidal flooding could make more energy dissipated as sensible heat (H_s) in summer, but as latent heat in winter in mangrove ecosystem. Energy closure ratio of mangrove ecosystem was reduced significantly during flooding days in winter, while summer was just the opposite, a higher energy closure ratio was obtained.

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