DOI: 10.1007/s11430-006-8163-z

A preliminary study on the heat storage fluxes of a tropical seasonal rain forest in Xishuangbanna

DOU Junxia[1,3,4], ZHANG Yiping[1], YU Guirui[2], ZHAO Shuangju[1], WANG Xin[1,4] & SONG Qinghai[1,4]

1. Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Kunming 650223, China;
2. Institute of Geographic Sciences and National Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
3. Research Centre for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China;
4. Graduate University of the Chinese Academy of Sciences, Beijing 100049, China

Correspondence should be addressed to Zhang Yiping (email: yipingzh@xtbg.ac.cn)

Received October 27, 2005; accepted March 10, 2006

Abstract In order to discuss the values and daily variation characteristics of heat storage fluxes in a tropical seasonal rain forest in Xishuangbanna, the sensible and latent heat storage flux within air column, canopy heat storage flux, energy storage by photosynthesis and ground heat storage above the soil heat flux plate, as well as the ratios of these heat storage fluxes to the net radiation in the cool-dry, hot-dry and rainy season were compared and analyzed based on the observation data of carbon fluxes, meteorological factors and biomass within this tropical seasonal rain forest from January 2003 to December 2004. The findings showed that heat storage terms ranged significantly in the daytime and weakly in the nighttime, and the absolute values of sensible and latent heat storage fluxes were obviously greater than other heat storage terms in all seasons. In addition, the absolute values of total heat storage fluxes reached the peak in the hot-dry season, then were higher in the rainy season, and reached the minimum in the cool-dry season. The ratios of heat storage fluxes to net radiation generally decreased with time in the daytime, moreover, the sensible and latent heat storage dominated a considerable fraction of net radiation, while other heat storage contents occupied a smaller fraction of the net radiation and the peak value was not above 3.5%. In the daytime, the ratios of the total heat storage to net radiation were greater and differences in these ratios were distinct among seasons before 12:00, and then they became lower and differences were small among seasons after 12:00. The energy closure was improved when the storage terms were considered in the energy balance, which indicated that heat storage terms should not been neglected. The energy closure of tropical seasonal rain forest was not very well due to effects of many factors. The results would help us to further understand energy transfer and mass exchange between tropical forest and atmosphere. Moreover, they would supply a research basis for studying energy closure at other places.

Keywords: heat storage flux, energy closure, tropical seasonal rain forest, Xishuangbanna.

Terrestrial ecosystems are the most important systems that play a great role in human being survival and sustainable development. As a critical component of terrestrial ecosystems, forests characterized by large area, tremendous biomass and huge carbon storage have a significant effect on global climate change. As one indispensable conditioner of atmospheric CO_2, forests serve as both a carbon sink when absorbing atmospheric CO_2 and fixing it in biomass through assimilation and a carbon source when releasing carbon in the form of CO_2 and CO into the atmosphere through the respiration of animals, plants and microbes, and the litterfall decomposition. Variations in carbon flux, mass exchange and energy transfer between the forest ecosystem and the atmosphere would influence forest plant growth and atmospheric CO_2 concentration. Therefore, studies about the characteristics and variations of greenhouse gases and energy flux between forest ecosystems and the atmosphere are the most important aspects in the field of forest ecosystem structure and functions.

Recently, eddy covariance measurements enable us to measure turbulent fluxes of heat, water vapor, and CO_2 over vegetation directly for a wide range of time scales from hours to years[1−3]. It provides a unique contribution to the study of the environmental, biological and climatological controls of net surface exchange between vegetation and the atmosphere[4−8]. However, eddy covariance technique is limited to use and easily related to measurement errors by many factors, such as vegetation height, footprint area, boundary-layer stability, sensor heights and separation, frequency response, alignment problems, and interference from tower or instrument-mounting structures. So independent methods of evaluating the reliability of the eddy covariance measurements are highly desirable. One method of independently evaluating scalar flux estimates from eddy covariance is energy balance closure[3,4,9−17]. Energy balance closure, a formulation of the first law of thermodynamics, requires that the sum of the estimated latent (*LE*) and sensible (*H*) heat flux be equivalent to all other energy sinks and sources:

$$LE + H = R_n - G - S - M, \quad (1)$$

where R_n is the net radiation, G the heat flux into the soil substrate, S the rate of change of heat storage (air and biomass) between the soil surface and the level of the eddy covariance instrumentation, and M the sum of all additional energy sources and sinks. Typically, M is neglected as a small term, and an imbalance between the remaining independently measured terms on the left- and right-hand sides of eq. (1) is often an issue for many land surface types, owing to several reasons, including: (1) sampling errors associated with different measurement source areas for the terms in eq. (1); (2) a smaller area of footprint; (3) the loss of low and/or high frequency contributions to the turbulent flux; (4) the neglected horizontal and/or vertical advection of heat and water vapor; and (5) the neglected energy sinks. The imbalance is often present and surface energy fluxes ($LE + H$) are frequently (but not always) underestimated by about 10%−30% relative to estimates of available energy ($R_n - G - S$)[12,13,15,17−21]. The scalar flux measured by eddy covariance technology needs to correct when energy imbalance was above 20%; otherwise, scalar flux is easily to over- or underestimated. Accordingly, it is very difficult to objectively evaluate the process of energy transfer and mass exchange between the ecosystems and atmosphere[17].

The role of heat storage terms between the soil surface and the level of the eddy covariance instrumentation is usually neglected in the surface energy balance of vegetation. This analysis is an attempt to account for not only the sensible and latent heat storage flux within air column, but also ground heat storage above the soil heat flux plate, the storage of heat by the canopy biomass and water content, as well as the net energy flux consumed in the photosynthetic process. Data from a research flux tower in a tropical seasonal rain forest in Xishuangbanna from January 2003 to December 2004 are used to evaluate these storage terms and their impact on the closure of the surface energy balance, which may provide vital insight into the process of energy transfer and mass exchange between tropical forest ecosystems and the atmosphere, and furthermore, supply reference for other studies about energy balance.

1 Materials and methods

1.1 Site description

This study was conducted in a tropical seasonal rain forest (21°55′39″N, 101°15′55″E, elevation 750 m) in the Menglun Forest Reserve in Mengla County, Yunnan Province. It is a permanent plot dedicated to long-term ecological research managed by the Xishuangbanna Tropical Rainforest Ecosystem Station, the Chinese Academy of Sciences. The mean annual air temperature is 21.7℃ and annual rainfall is 1487 mm, of which 87% occurs in the rainy season (May—October) and 13% in the dry season (November—April). Dense fog layers commonly occur during the dry season which is further divided into a cool-dry season from November to February, and a hot-dry season from March to April[22].

The forest structure at the study site can be divided into three general tree layers that are represented by different species. More than 70% of all individuals of trees occur in tree layer C (below 16 m), which has small evergreen trees and juveniles of species from the upper tree layers (above 16 m). Tree layer B, which is between 16—30 m, consists of a mixture of evergreen and deciduous species, such as *Barringtonia macrostachya*, *Gironniera subaequalis*, and *Sloanea cheliensis*. Tree layer A, having a canopy height over 30 m, is dominated by *Pometia tomentosa* and *Terminalia myriocarpa*. Many species of algae, lichens, mosses and ferns comprise the epiphytes communities. The woody climbers, such as *Byttneria integrifolia* and *Gnetum montanum* are also common at the study site[23].

The height of the meteorological tower at the observation site is 72 m. The sensors of eddy flux were installed at 48.8 m and 4.8 m above ground level, respectively. The flux measurement system consisted of a fast-response three-dimensional sonic anemometer-thermometer (CSAT3, CAMPBELL, USA) and a fast-response open-path infrared gas analyzer (LI-7500, LI-COR, Inc., Lincon, NE, USA). Samples were recorded at 10 Hz by two CR5000 data loggers (Model CR5000, Campbell Scientific) and 30 min mean values were calculated. In addition, a routine meteorological gradient system was installed on the tower, including 7-level air temperature, and relative humidity sensors (HMP45C), with the heights of 4.2, 16.3, 26.2, 36.5, 42.0, 48.8 and 69.8 m. Net radiation was measured with 4-components method (CM11, KIPP&ZONEN, the Netherlands) at 41.6 m and an infrared thermometer was installed at 52.0 m above the ground. Soil temperatures were measured at nine depths (0, 5, 10, 15, 20, 40, 60, 80, 100 cm) by thermocouples (105 T and 107-L, Campbell Scientific). Sensors (TDR, CS616_L, Campbell) of soil water contents were positioned at 5, 20, 40 cm depth. Two soil heat flux plates were buried at 5 cm depth. These factors were sampled at 0.5 Hz and the data were stored in the data loggers. 30 min averaged data were also calculated by the data loggers and stored. These measurements were started from November, 2002 and data of clear days in 2003 and 2004 were used in this paper.

1.2 Study methods

The total rate of energy storage (S) in a column extending from the ground surface to the height of the eddy covariance system being located (48.8 m) was calculated as[24,25]

$$S = S_s + S_a + S_e + S_c + S_p. \tag{2}$$

All components in eq. (2) are expressed as heat storage change fluxes, where S_s refers to ground heat storage above the soil heat flux plate, S_a and S_e are the sensible and latent heat contributions in the air-column below the eddy covariance system, S_c is canopy heat storage in biomass and water content, and S_p is the energy consumed in photosynthesis.

The ground heat storage above the soil heat flux plate was calculated as

$$S_s = C_s \frac{\Delta T_s}{\Delta t} Z, \tag{3}$$

where T_s is the average values of soil temperature measured at 0 and 5 cm, t is time (in this case $\Delta t = 0.5$ h), Z is the depth above the soil heat flux plates (5 cm) and C_s is the soil heat capacity calculated from

$$C_s = \rho_b c_{sd} + \theta_v c_{sw}, \tag{4}$$

where ρ_b is the bulk density of the soil, and here a soil bulk density mean value of 1.08 $g \cdot cm^{-3}$ was used, as determined by cylindrical core of soil at 0—10 cm depths; c_{sd} and c_{sw} are the specific heats of the dry mineral soil ($c_{sd} = 0.85\ J \cdot g^{-1} \cdot ℃^{-1}$) and the soil water ($c_{sw} = 4.19\ J \cdot g^{-1} \cdot ℃^{-1}$), respectively; and θ_v is the volumetric water content (%) in the soil measured using CS616_L Water Content Reflectometers (CSI, Logan, UT).

The sensible heat storage flux in the air within the column was calculated as follows:

$$S_a = \int_0^{z_r} \rho c_p \frac{\partial T}{\partial t} dz \cong \rho c_p \sum_{i=1}^{n} \left(\frac{\Delta T_a}{\Delta t} \Delta z_i \right), \quad (5)$$

where ρ is the air density, c_p is the specific heat of air (c_p = 1.012 J · g^{-1} · ℃$^{-1}$), z_r is the height of eddy flux system measurement (48.8 m), T is air temperature in the air-column below z_r, and T_a is a representative layer-average of T in each of several layers, Δz_i, below z_r. In this study, T_a was measured at six levels (4.2, 16.3, 26.2, 36.5, 42.0, 48.8 m) and S_a was calculated by summing eq. (5) through the six levels of temperature measurements using half an hour increments.

The latent heat storage flux was calculated as

$$S_e = \int_0^{z_r} \frac{\rho c_p}{\gamma} \frac{\partial e}{\partial t} dz \cong \frac{\rho c_p}{\gamma} \sum_{i=1}^{n} \left(\frac{\Delta e_i}{\Delta t} \Delta z_i \right), \quad (6)$$

where e is water vapor pressure, calculated from T_a and relative humidity measurements from the HMP45C profile; γ is the psychrometric constant (0.0007947). Similar to S_a, eq. (6) was calculated for the six levels to 48.8 m and summed.

The rate of canopy heat storage was calculated as

$$S_c = \frac{L \sigma_c c_c \frac{\Delta T_c}{\Delta t}}{1 - W_w}, \quad (7)$$

where L is leaf area index and measured by using a Li-2000 each month; σ_c is the specific leaf weight (mass of dry leaves per square meter of leaf) (85 g · m^{-2}); W_w is the water content on a wet mass basis (67%); and $\frac{\Delta T_c}{\Delta t}$ is canopy temperature change per half an hour. The leaf specific heat was calculated as

$$c_c = 0.67 c_w + 0.33 c_G, \quad (8)$$

where c_w and c_G were the specific heat of water and glucose, respectively (c_w = 4.19 J · g^{-1} · ℃$^{-1}$; c_G = 1.26 J · g^{-1} · ℃$^{-1}$); T_c is measured using the infrared thermometer mounted at 52 m.

The rate of energy consumption during photosynthesis in the chemical formation of carbon bonds was calculated as

$$S_p = -F_c C, \quad (9)$$

where F_c is the CO_2 flux in mg · m^{-2} · s^{-1}, and C is the photosynthetic energy conversion factor (11.2 W · mg^{-1} · s) with a sign convention of negative F_c representing CO_2 uptake. In addition, the calculation of any S_p term was only performed when F_c was negative (net carbon uptake) and with positive R_n.

Data of all variables in formulas mentioned above were obtained by eddy covariance system and routine meteorological system, except for parameters having been given values or measurement methods. The measurements were started from November, 2002, and the data of 2003 and 2004 were used in this paper.

2 Results and analyses

2.1 Daytime variations of heat storage terms

(i) Heat storage in the air. The sensible heat storage flux in the air (S_a) within the column presented one peak and one trough tendency during a day in the cool-dry season, with values ranging significantly in the daytime and weakly in the nighttime (Fig. 1). Before 09:00 AM, air temperature was relatively stable, which resulted in the lower values and smaller variations of S_a; later, the air temperature increasing gradually and the radiation fog dying away made S_a enhance correspondingly after 09:00 AM. Although the maximum values of T_a in each of several layers occurred from 14:00 to 16:00 PM one after the other, the greater values of the rate of change in T_a almost appeared during the period from 11:00 AM to 13:00 PM. So S_a reached the peak of 37.6 W · m^{-2} at 11:30 AM; after that, T_a of some layers kept on increasing before 15:00 PM, even until 16:00 PM. However, the rate of variation in T_a decreased gradually, which led to S_a decreasing and approaching zero at 15:00 PM. Moreover, S_a continued to decrease after 15:00 PM, associated with T_a reducing. The minimum value of S_a occurred at 17:30 PM, with a value of −33.7 W · m^{-2}. Furthermore, lower S_a persisted for period of time for sun setting promoted a decrease in T_a. S_a remained relatively constant after 21:00 PM.

Daily variation of S_a in the hot-dry and rainy seasons was similar to that in the cool-dry season, although the values of S_a were changed from positive to negative earlier in the morning and from negative to positive later in the dusk in the hot-dry and rainy seasons than that in the cool-dry season as fog disappeared earlier and solar angle was greater in the

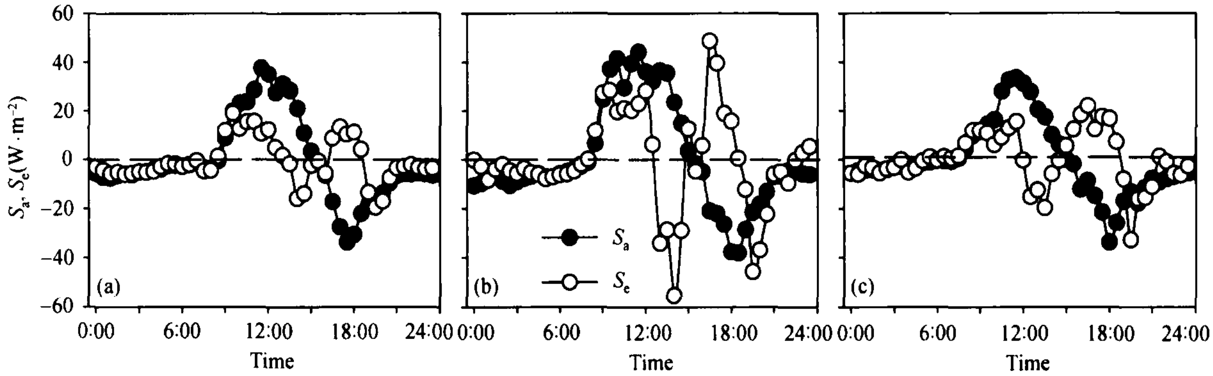

Fig. 1. Daily variation of S_a and S_e in the cool-dry (a), hot-dry (b) and rainy seasons (c).

hot-dry and rainy seasons. In addition, higher S_a remained in a relatively long period of time in the hot-dry season. S_a also reached a peak at 11:30 AM in the hot-dry and rainy seasons, with the values of 44.2 and 33.6 W·m^{-2}, respectively. The minimum values of S_a were −33.9 and −38.1 W·m^{-2} in the hot-dry and rainy season, separately, appearing at 18:00 PM.

Daily variation of S_e presented two peaks and two troughs tendency in each season, characterized by values varying significantly in the daytime and weakly in the nighttime (Fig. 1). In the cool-dry season, water vapor pressure (*e*) continually decreased in the nighttime because of fog occurrence, with the minimum value of *e* in each of several layers approximately appearing at 08:00 AM, except for *e* of 48.8 m above the ground. The value of *e* increased rapidly after 08:00 AM, consistent with fog disappearing gradually and fog interception evaporating, which caused S_e to increase correspondingly, with a peak value of 19.2 W·m^{-2} existing at 09:30 AM in the cool-dry season. After 12:00 AM, *e* increased slowly and even began to decrease due to fog disappearing drastically and fog interception exhausting completely. So the first minimum value of S_e appeared at 14:00 PM, with a value of −15.9 W·m^{-2}. At a later time, air temperature further increasing promoted air to accommodate more water vapor that conduced to the second maximum value of S_e occurring at 17:00 PM, with a value of 13.5 W·m^{-2}. Then, the air temperature decreasing and relative humidity increasing induced that the declining rate of *e* achieved a peak at 19:30 PM, with a minimum value of S_e for −19.4 W·m^{-2}. From 21:00 PM to 08:00 AM of the next day, S_e kept stable, and moreover, the absolute values of S_e were lower and hardly beyond 5 W·m^{-2}.

The range of S_e was greater in the hot-dry season than that in the cool-dry and rainy seasons. The two maximum values of S_e were 28.5 and 48.6 W·m^{-2}, occurring at 09:30 AM and 16:30 PM, respectively, while the two minimum values of S_e were −55.6 and −45.8 W·m^{-2}, appearing at 14:00 and 19:30 PM, separately. The reason for S_e characterized by a greater range in the hot-dry season is that the higher mean air temperature and smaller rainfall resulted in a lower relative humidity in this season. Furthermore, canopy trees shed more leaves in March and April than in other months over a year and then sparse canopy had a weaker effect on forest microclimate, which caused water vapor pressure to increase or decrease rapidly.

In the rainy season, although air temperature is also higher, rainfall is abundant and relative humidity is greater, therefore, there is a relatively weaker capability for air to further accommodate water vapor, which caused that the range of S_e was moderate and it was higher than that in the cool-dry season, but lower than that in the hot-dry season. In addition, water vapor pressure increased slowly after sunrise, owing to little influence by heavy fog. So it was only in 11:30 AM that S_e reached its first peak, two hours later than in other seasons, with the maximum value of 15.5 W·m^{-2}. The first minimum value of S_e was −19.8 W·m^{-2}, while it occurred at 13:30 PM, half an hour earlier than in other seasons. The second maximum and minimum values of S_e were 21.9 and −32.8 W·m^{-2}, respectively, and the time of their appearance was the same as that in the hot-dry season.

(ii) Canopy heat storage. Daily variation of S_c presented one peak and one trough tendency during a day in every season, similar to that of S_a and also characterized by a greater range in the daytime and a smaller change in the nighttime (Fig. 2). The values of S_c were always lower in each season, moreover, the absolute values of S_c were never higher than 1 W · m^{-2} before 08:00 AM and after 20:00 PM, and even in the daytime, S_c ranged from −5.3—3.9 W · m^{-2}, −3.7—3.6 W · m^{-2} and −4.0—4.0 W · m^{-2} in the cool-dry, hot-dry and rainy season, respectively. Differences in values of S_c were weaker among seasons.

(iii) Energy storage by photosynthesis. The energy consumption during photosynthesis (S_p) was considerably lower in every season, and the differences in S_p among seasons were also smaller. In the cool-dry and hot-dry seasons, S_p reached a peak at 13:00 PM, with the values of 4.8 and 5.1 W · m^{-2}, respectively; while in the rainy season, the maximum value of S_p occurred earlier (12:00 AM) and S_p had a higher peak value of 5.4 W · m^{-2} (Fig. 2).

(iv) The ground heat storage above the soil heat flux plate. The ground heat storage above the soil heat flux plate (S_s) showed one peak variation in the course of a day in every season. Compared with other kinds of heat storage, the absolute values of S_s were obviously lower than that of S_a and S_e, but slightly higher than that of S_p and S_c (Fig. 3).

Influenced by sparse canopy, the rate of increase or decrease in soil temperature was the fastest in the hot-dry season over a year, with a maximum value of S_s being 11.2 W · m^{-2}, distinctly higher than 5.6 W · m^{-2} in the cool-dry season and 6.8 W · m^{-2} in the rainy season, respectively. In the nighttime, most values of S_s kept around −3.0 W · m^{-2} in the hot-dry season and the minimum value was −3.6 W · m^{-2}; while the values of S_s remained around −2.0 W · m^{-2} in the cool-dry and rainy seasons, with a minimum value of −2.5 and −2.7 W · m^{-2}, respectively.

(v) Total heat storage. As illustrated by Fig. 4, S usually ranged from −20 to 0 W · m^{-2} during the period of 21:00 PM to 08:00 AM of the next day, and moreover, there existed little difference in S among seasons. Over a year, the greatest range of S in the daytime

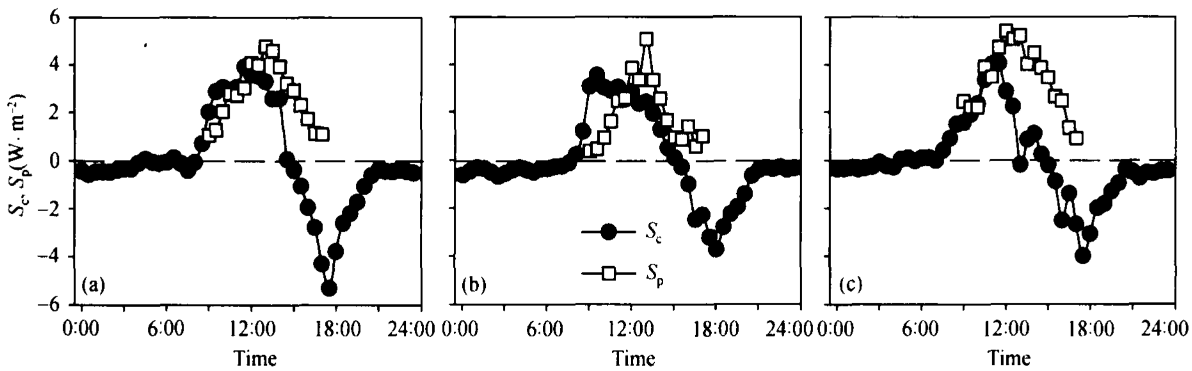

Fig. 2. Daily variation of S_c and S_p in the cool-dry (a), hot-dry (b) and rainy seasons (c).

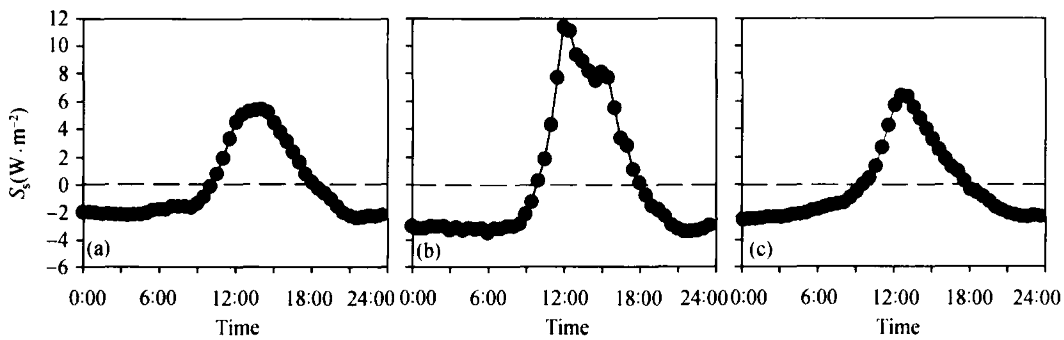

Fig. 3. Daily variation of S_s in the cool-dry (a), hot-dry (b) and rainy seasons (c).

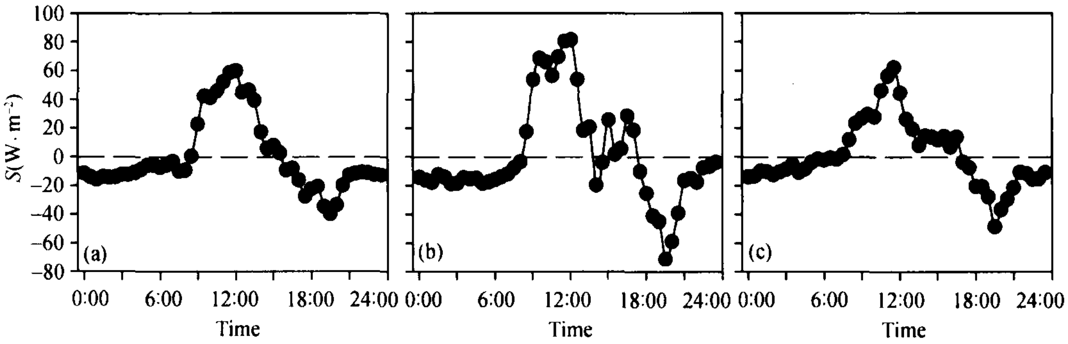

Fig. 4. Daily variation of S in the cool-dry (a), hot-dry (b) and rainy seasons (c).

appeared in the hot-dry season; however, the cool-dry and rainy seasons were alike in the daytime range of S, with a little lower range in the cool-dry season. In the cool-dry season, S had a maximum and minimum value of 59.9 and –39.9 $W \cdot m^{-2}$, respectively; while the maximum and minimum values turned into 81.5 and –71.3 $W \cdot m^{-2}$ in the dry-hot season. As for the rainy season, S had a peak value of 62.1 $W \cdot m^{-2}$ and a minimum value of –48.6 $W \cdot m^{-2}$, separately.

2.2 *The ratios of heat storage terms to net radiation*

(i) Heat storage in air column. Owing to differences in diurnal variations between S_a and S_e, the ratios S_a/R_n had a gradual decrease trend with the time in all the seasons; however, S_e/R_n was characterized by higher values in the morning and dusk and lower values in other period of time (Fig. 5). S_a and S_e dominated a considerable fraction of R_n in each season, and moreover, the maximum ratio all occurred before 10:00 AM. The peak values of ratios S_a/R_n and S_e/R_n were 18.2% and 18.8% in the cool-dry season, 29.4% and 26.2% in the hot-dry season, and 11.5% and 11.9% in the rainy season, respectively. On the whole, the daytime ratios of S_a/R_n and S_e/R_n were the greatest in the hot-dry season, and the lowest in the rainy season. In addition, compared with S_e, S_a always occupied a higher fraction of R_n except for individual time in every season.

(ii) Canopy heat storage. Generally speaking, S_c occupied a smaller fraction of the net radiation (R_n) in every season (Fig. 6). The ratio S_c/R_n presented a gradual decrease throughout the daytime in the cool-dry and hot-dry seasons, with the maximum values all below 3.5%. In the rainy season, similar diurnal trend was observed for the ratio S_c/R_n but the peak value was only 1.6%.

(iii) Energy storage by photosynthesis. S_p comprised a small and stable fraction of the R_n throughout a year (Fig. 6). In the cool-dry season, the ratios were all above 1.0% before 11:00 AM, with the peak value of 1.7% occurring at 09:00 AM. After 11:00 AM, the ratios mainly ranged between 0.5% and 1.0%. The maximum ratio was only 1.0% in the hot-dry season; moreover, the S_p never had a fraction of R_n exceeding 0.5% before 10:00 AM and after 14:00 PM. Diurnal variation of ratio S_p/R_n in the rainy season was similar

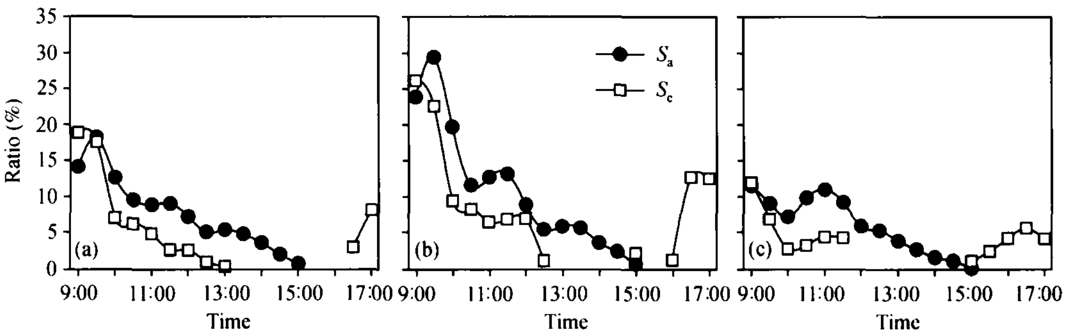

Fig. 5. Diurnal variation of ratios of S_a/R_n and S_e/R_n in the cool-dry (a), hot-dry (b) and rainy seasons (c).

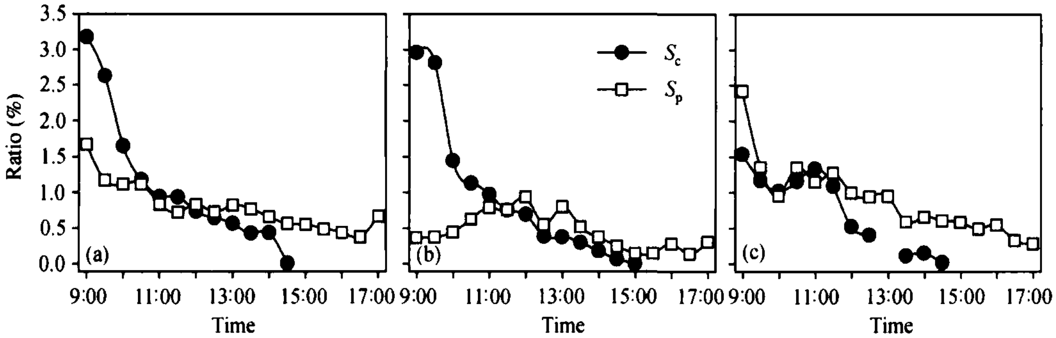

Fig. 6. Diurnal variation of ratios of S_c/R_n and S_p/R_n in the cool-dry (a), hot-dry (b) and rainy seasons (c).

to that in the cool-dry season, with the peak value of 2.4% also appearing at 09:00 AM; moreover, the ratios were above 1.0% but below 1.5% before 13:00 PM, and after that time, they usually varied from 0.5% to 1.0%.

(iv) The ground heat storage above the soil heat flux plate. Similar to S_c and S_p, S_s still dominated a small fraction of R_n in every season (Fig. 7). The ratio S_s/R_n kept constant in the cool-dry season, with values always approaching 1.0% in most of the daytime. It had a relatively higher range in the hot-dry season, characterized by a quick increase before 12:00 AM; however, the maximum value was only 2.8%. In the rainy season, the ratio of S_s to R_n showed a first increase and then a decrease trend. Ratios were never over 1.0% in the course of a day except for the period from 11:00 AM to 13:00 PM (the maximum value was 1.3%).

(v) Total heat storage. Before 12:00 AM, differences of ratios S/R_n were greater among seasons; ratios were all above 10% in the cool-dry season, with a peak value of 38.8%; while S possessed over 20% fraction of R_n in the hot-dry season and the maximum value reached 54.3%. Although it was similar to the cool-dry season that ratios were higher than 10% in the rainy season before 12:00 AM, the peak value was 26.5%, lower than that in the cool-dry season. After 12:00 AM, ratios were all below 10% and differences in ratios were smaller among seasons (Fig. 8).

2.3 *Energy balance analysis*

The effect of the storage terms on the surface energy balance was examined by comparing the sum of H, LE, and G with and without the total storage terms against R_n for the cool-dry, hot-dry and rainy seasons (Table 1). When the storage terms were included in the surface energy balance, the slope from simple linear regression was all increased in each season, with the greatest value of 5% in the cool-dry season and the lowest value of 2% in the rainy season.

Table 1 Energy balance analysis in every season

Season	Regression equation	Correlation coefficient
Cool-dry	$LE+H = 0.52\ (R_n - G)$	0.88
	$LE+H = 0.56\ (R_n - G - S)$	0.90
Hot-dry	$LE+H = 0.55\ (R_n - G)$	0.87
	$LE+H = 0.58\ (R_n - G - S)$	0.88
Rainy	$LE+H = 0.55\ (R_n - G)$	0.86
	$LE+H = 0.57\ (R_n - G - S)$	0.85

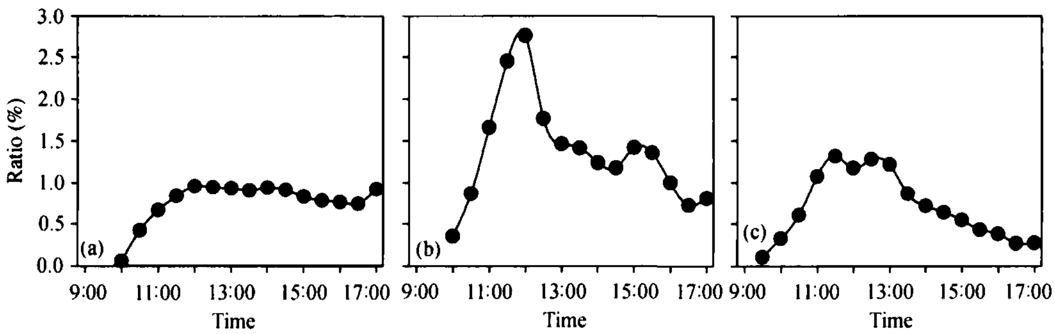

Fig. 7. Diurnal variation of ratios of S_s/R_n in the cool-dry (a), hot-dry (b) and rainy seasons (c).

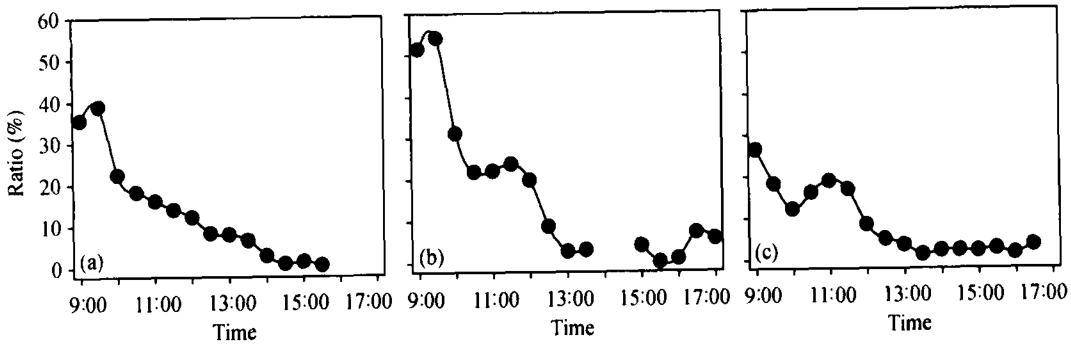

Fig. 8. Diurnal variation of ratios of S/R_n in the cool-dry (a), hot-dry (b) and rainy seasons (c).

3 Discussion

The measurements of the canopy heat storage terms were mainly developed in the researches on temperature forest or agricultural ecosystems. Meyers and Hollinger[26] ever accounted for not only the heat storage above the soil heat flux plate in the soil, but also the heat storage by the canopy biomass and water content, as well as the net energy flux consumed in the photosynthetic process in fully grown maize and soybean crops for two years. The results of our paper revealed that, in comparison with maize crop, the heat storage from canopy, ground and photosynthesis was generally lower in a tropical seasonal rain forest of Xishuangbanna, with canopy and photosynthesis heat storage terms hardly exceeding 5 $W \cdot m^{-2}$ and the maximum ratios of them to net radiation never going beyond 3.5% in the daytime. For maize crop, the ground heat storage peaked around 09:00 LST with an equivalent flux of 40 $W \cdot m^{-2}$ as soils quickly warmed from both the increased air temperatures and the penetrating solar radiation. For the same time interval, plant heat and photosynthesis storage were about the same magnitude at 20 $W \cdot m^{-2}$, and moreover, the photosynthesis storage term peaked at midday with fluxes approaching 30 $W \cdot m^{-2}$. The combined total of all storage terms was nearly 80 $W \cdot m^{-2}$ around 09:00 LST, which was a significant fraction (20%) of the net radiation. For soybean crop, the magnitudes for the individual storage terms were similar to those of our study site. For example, early in the day, ground storage was the largest at 17 $W \cdot m^{-2}$, followed by photosynthetic storage at 10 $W \cdot m^{-2}$ and canopy storage at 7 $W \cdot m^{-2}$ from 06:00 to 10:00 AM.

Heat storage terms were ever measured by Oliphant *et al.*[25] in a temperate deciduous forest from 1998 to 2001. Similar to that of our study site, diurnal patterns of sensible heat storage presented one peak and one trough trend in every month, with little difference among months. Moreover, sensible heat storage generally reached the peak during the time from 10:00 to 11:00 AM, with the maximum value approaching 30 $W \cdot m^{-2}$; while in the nighttime, sensible heat storage usually ranged from −10 to 0 $W \cdot m^{-2}$. Differences in latent heat storage were greater not only between this forest and tropical seasonal rain forest in our study site, but also among months. Latent heat storage was higher during the period from May to September when plants growed. In addition, daily latent heat storage had a trend of two peaks, with values ranging greater in the daytime and the peak being approximately 20 $W \cdot m^{-2}$. Latent heat storage was lower in the nighttime, with values being usually −10 $W \cdot m^{-2}$.

In addition, several heat storage terms during preleaf and full-leaf periods in a boreal forest were ever measured by Blanken *et al.*[24]. The results revealed that the daytime average preleaf total heat storage of 18 $W \cdot m^{-2}$ was largely composed equally of the sensible (9 $W \cdot m^{-2}$) and latent heat storage (8 $W \cdot m^{-2}$). When the canopy was leafed, however, daytime postleaf total heat storage of 22 total heat storage was composed mainly of bole heat storage (8 $W \cdot m^{-2}$), followed by sensible heat storage (6 $W \cdot m^{-2}$), photosynthesis heat storage (5 $W \cdot m^{-2}$), latent heat storage (2 $W \cdot m^{-2}$) and finally canopy heat storage (1 $W \cdot m^{-2}$), respectively.

Although there existed great difference among research results due to study sites belonging to different ecosystems or possessing distinct characteristics of community structure, all conclusions indicated that heat storage terms should not been neglected. Firstly, the total heat storage comprised a significant fraction of net radiation in the daytime. The results studied by Meyers and Hollinger[26] indicated that when considered separately on a scale analysis, the storage fluxes were relatively small after 09:00 CST compared to the other terms in the total surface energy balance (*H*, *LE*, and *G*). However, the combined storage flux was significant and at times constituted a significant fraction of the available energy. The storage terms were the highest and comprised a greater fraction of net radiation in the period between 06:00 and 12:00 AM LST. For this time period, the average storage fraction was 13.6% and 7.8% for maize and soybean, respectively. The ratio of total heat storage to net radiation was 8% and 11% during the preleaf and full-leaf periods respectively in a boreal aspen forest[24]. In our study site, the total heat storage terms were shown to account for 13.3% of the total net radiation in the cool-dry season, 17.3% in the hot-dry season and 8.8% in the rainy season, respectively, during the daytime from 09:00 AM to 17:00 PM; moreover, the fraction reached 22.4%, 32.1% and 16.7% separately in the cool-dry, hot-dry and rainy season before 12:00 AM. Secondly, when the heat storage terms were considered, the extent of energy balance closure was improved more or less. For example, Meyers and Hollinger[26] reported that when all of the storage terms were considered, for maize, the slope of the regression between net radiation and the sum of the energy components increased from 84% to 94%; while for soybean, the slope increased from 90% to 97%. Heat storage terms also generated a 2.5% improvement in closure in a temperate deciduous and a boreal aspen forest respectively[24,25], which is similar to that in a tropical seasonal rain forest in Xishuangbanna. Energy closure in our study site was relatively lower than in other places. Maybe it is caused by many factors such as non-flat terrain, smaller footprint, and neglected horizontal advection, etc. So it needs to further evaluate the quality of energy balance closure under a range of conditions and identify possible causes for lack of closure in this tropical seasonal rain forest.

Acknowledgements This research was supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01), the National Basic Research Program of China (Grant No. 2002CB412501), and the Natural Science Foundation of Yunnan Province, China (Grant No. 98C098M). We give thanks to Xishuangbanna Tropical Rainforest Ecosystem Station, the Chinese Academy of Sciences for help in this project. We offer special thanks to Associate Professor Sha Liqing for assistance with the paper.

References

1 Foken T, Wichura B. Tools for quality assessment of surface-based flux measurements. Agric For Meteorol, 1996, 78: 83—105

2 Baldocchi D D, Meyers T P. On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and gaseous deposition fluxes over vegetation. Agric For Meteorol, 1998, 90: 1—26

3 Aubinet M, Grelle A, Ibrom A, et al. Estimates of annual net carbon and water exchange of European forests: The EUROFLUX methodology. Adv Ecol Res, 2000, 30: 113—175

4 Constantin J, Grelle A, Ibrom A, et al. Flux partitioning between understorey and overstorey in a boreal spruce/pine forest determined by the eddy covariance method. Agric For Meteorol, 1999, 98-99: 629—643

5 Baldocchi D D, Kelliher F, Black T A, et al. Climate and vegetation controls on boreal zone energy exchange. Glob Change Biol, 2000, 6(Suppl.1): 69—83

6 Berbigier P, Bonnefond J, Mellmann P. CO_2 and water vapour fluxes for 2 years above Euroflux forest site. Agric For Meteorol, 2001, 108: 183—197

7 Serca D, Guenther A, Klinger L, et al. EXPRESSO flux measurements at upland and lowland Congo tropical forest site. Tellus, 2001, 53B(3): 220—234

8 Vourlitis G L, Filho N P, Hayashi M M, et al. Seasonal variations in the net ecosystem CO_2 exchange of a mature Amazonian transitional tropical forest (cerradão). Funct Ecol, 2001, 15: 388—395

9 Anderson D E, Verma S B, Rosenberg N J. Eddy correlation measurements of CO_2, latent heat and sensible heat fluxes over a crop surface. Bound-Layer Meteor, 1984, 29: 263—272

10 Verma S B, Baldocchi D D, Anderson D E, et al. Eddy fluxes of CO_2, water vapor, and sensible heat over a deciduous forest. Bound-Layer Meteor, 1986, 36: 71—91

11 Mahrt L. Flux sampling errors for aircraft and towers. J Atmos Ocean Technol, 1998, 15: 416—429

12 Hollinger D Y, Hollinger D Y, Goltz S M, et al. Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. Glob Change Biol, 1999, 5: 891—902

13 Anthoni P, Law B E, Unsworth M J. Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem. Agric For

Meteorol, 1999, 95: 151−168

14 Goldstein A H, Hultman N E, Fracheboud J M, et al. Effects of climate variability on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). Agric For Meteorol, 2000, 101: 113−129

15 Wilson K B, Boldocchi D D. Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. Agric For Meteorol, 2000, 100: 1−18

16 Schmid H P, Grimmond C S B, Cropley F, et al. Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the mid-western United States. Agric For Meteorol, 2000, 103: 357−374

17 Wilson K, Goldstein A, Falge E, et al. Energy balance closure at FLUXNET sites. Agric For Meteorol, 2002, 113: 223−243

18 Wright I R, Gash J H C, da Rocha H R, et al. Dry season micrometeorology of central Amazonian ranchland. Q J R Meteorol Soc, 1992, 118: 1083−1099

19 Goulden M L, Munger J W, Fan S M, et al. Measurement of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy. Glob Change Biol, 1996, 2: 169−182

20 Kelliher F M, Hollinger D Y, Schulze E D, et al. Evaporation from an eastern Siberian larch forest. Agric For Meteorol, 1997, 85: 135−147

21 Jarvis P G, Massheder J M, Hale S E, et al. Seasonal variation of carbon dioxide, water vapor, and energy exchanges of a boreal spruce forest. J Geophys Res, 1997, 102D: 28953−28966

22 Zhang K Y. Abecedarian analyses on the characteristics and take shape factors of climate in the south of Yunnan. Acta Meteorologica Sinica (in Chinese), 1966, 33(2): 210−230

23 Ren Y H, Cao M, Tang J W, et al. A comparative study on litterfall dynamics in a seasonal rain forest and a rubber plantation in Xishuangbanna, SW China. Acta Phytoecologica Sinica, 1999, 23(5): 418−425

24 Blanken P D, Black T A, Yang P C, et al. Energy balance and canopy conductance of a boreal aspen forest: Partitioning overstory and understory components. J Geophys Res, 1997, 102(24): 28915−28927

25 Oliphant A J, Grimmond C S B, Zutter H N, et al. Heat storage and energy balance fluxes for a temperate deciduous forest. Agric For Meteorol, 2004, 126: 185−201

26 Meyers T P, Hollinger S E. An assessment of storage terms in the surface energy balance of maize and soybean. Agric For Meteorol, 2004, 125: 105−115