Evaluation and estimation of canopy heat storage fluxes in an apple orchard

Daiyu ITO*, †, Sachinobu ISHIDA**, and Dai MATSUSHIMA***

*Teaching and Research Center for Bio-coexistence, Faculty of Agriculture and Life Science,
Hirotsuki University, 7–1, Shimobukuro, Fujisaki, Fujisaki, Aomori, 038–3802, Japan

**Graduate School of Science and Technology, Hirotsuki University,
Bunkyo-cho, Hirotsuki, Aomori, 036–8561, Japan

***Faculty of Engineering, Chiba Institute of Technology, Tsudanuma, Narashino, Chiba, 275–0016, Japan

Abstract

To precisely evaluate the impact of canopy heat storage on the energy balance of an apple orchard, heat storage flux and its diurnal changes were examined by observation during both growing and sprouting periods. The majority of canopy heat storage was trunk heat storage, followed by sensible and latent heat storages, while the leaf heat storage was negligible. The canopy heat storage flux peaked between 0700 and 0930 and bottomed out at around 1800. The range of diurnal flux was larger in the sprouting period than in the growing period, and likewise on days of higher solar radiation. It reached 66 Wm^{-2} on fine days in the sprouting period. By taking *HS* into account, the energy closure ratio for the eddy covariance method increased by 1.03 and 1.16 times in daytime and nighttime, respectively, and this increase was generally thought to improve the energy imbalance. The canopy heat storage flux could be well estimated from the difference of air temperature above the canopy at present and an hour before (RMSE 7 Wm^{-2}).

Key words: Energy balance closure, Fruit orchard, Micrometeorology, Sensible heat, Trunk.

1. Introduction

In recent years, although flux observations have been conducted at various sites all over the world to clarify carbon and/or water budgets, serious problems remain concerning the reliability of the observation. These include the energy imbalance in the eddy covariance method, in which the summation of the sensible heat flux (*H*; Wm^{-2}) and the latent heat flux (*IE*; Wm^{-2}) obtained by the turbulent observation does not satisfy the following energy balance equation:

$$H + IE = Rn - G - HS \quad (1)$$

where *Rn* (Wm^{-2}) and *G* (Wm^{-2}) represent the net radiation above the canopy and the soil heat storage flux at the ground surface, respectively. *HS* (Wm^{-2}) is the residual heat storage fluxes in the canopy other than the soil, consisting mainly of trunk, leaf, sensible,

latent and photosynthetic heat storages (Oliphant *et al.*, 2004).

Wilson *et al.* (2002) analyzed the results of flux observations at 22 sites for 50 years which had been conducted by the eddy covariance method, and found that the mean energy closure ratio, $(H+IE)/(Rn-G-HS)$, usually fell below 1 (mean of 0.84). Since the cause of this imbalance cannot be simply explained by the systematic observational error in *Rn*, *G*, and *HS* (Twine *et al.*, 2000), it is very probable that the *H* and *IE* were underestimated for some reasons, such as advection, measurement errors in sonic anemometers (Gash and Dolman, 2003), and a loss of low frequency components (Cava *et al.*, 2008). Therefore, *H* and *IE* are often corrected so that equation (1) is satisfied, and this correction is often also applied to the CO_2 flux (Twine *et al.*, 2000; Barr *et al.*, 2007). If we are to correct turbulent fluxes accordingly, the energy terms of *Rn*, *G*, and *HS* must be accurately measured.

Also, in the Bowen ratio-energy budget method, the precision of calculated *H*, *IE* and CO_2 fluxes

Received; May 6, 2010.

Accepted; October 3, 2010.

†Corresponding Author: daiyu@cc.hirosaki-u.ac.jp

depend greatly on the accuracy of Rn , G , and HS because these fluxes are all determined in proportion to $(Rn-G-HS)$.

Among Rn , G , and HS , HS is generally the smallest and moreover very laborious to evaluate correctly because many additional sensors must be equipped in the canopy to measure HS . For this reason, HS has often been neglected in herbaceous communities. However, in forest communities, HS is larger than that in herbaceous communities; by neglecting HS , the energy closure ratio was reported to decrease by 0.03 to 0.06 (Miura *et al.*, 2003), 0.08 to 0.09 (Michiles and Gielow, 2008), 0.10 (Ohkubo *et al.*, 2006), or 7% (Wilson *et al.*, 2002).

The authors have conducted flux observations in pear and apple orchards (Ito *et al.*, 2006; Ito *et al.*, 2009), but HS has not been taken into account since HS information related to fruit orchards remains very scarce. Although fruit orchards generally have lower canopy heights and less biomass compared to forests, HS should not be neglected if we are to observe CO_2 and H_2O fluxes as precisely as possible. In fact, in a corn field, the diurnal range in HS reached 30 Wm^{-2} (Meyers and Hollinger, 2004), despite having a lower canopy height compared to fruit orchards.

The objective of this study was to precisely evaluate the impact of HS on the energy balance of an apple orchard. We observed trunk, leaf, sensible, and latent heat storage fluxes of our flux site in both April and September, and analyzed their diurnal pattern of changes. A method of estimating HS from only the routine observations above and under the canopy, without conducting any additional observations within the canopy, is also proposed here.

2. Materials and Methods

2.1 Site description

Observations were conducted at and around the 9-m-tall flux tower at Fujisaki farm, Hirosaki University ($40^{\circ}39'N$, $140^{\circ}29'E$), located in Fujisaki town, Aomori prefecture. The tower exists in an experimental apple orchard with an area of 0.4 ha. The apple trees in the orchard were mainly 28 years old in 2007, 4 m in height, and trained with central leaders. The apple varieties planted were “Fuji”, “Starking Delicious”, and “Mutsu”. The inter-row and inter-tree distances were respectively 5.0m and 3.5 m, but were gradually extended to 7.0 m and 5.0 m by three rounds of alternate thinning conducted three times: partially

in April 2006, then mostly in February 2008, and finally around the flux tower in May 2008 after the observations of this study were completed.

Investigation of the trees that were thinned in 2006 revealed that the fresh weight of trunk and stem, and their water content were 11.06 kg m^{-2} and 52%, respectively. In November 2006 and 2007, just before defoliation, three trees were selected each year from the area with the original planting density, and were subjected to complete leaf picking. The fresh weight of the attached leaves, leaf water content and leaf area index (LAI) were 0.88 kg m^{-2} , 67%, and 4.40, respectively.

The experimental apple orchard described above was surrounded by another apple orchard containing trees of various varieties, and varying in shape and age. The apple orchard occupied approximately 90% of the area within 100 m from the tower, and 70% of that within 200 m from the tower. The remaining area was grassland or vegetable fields.

2.2 Observations

Routine observations were conducted continuously as follows. Air temperatures and relative humidities were measured by ventilated thermometer/hygrometers (Vaisala, HMP233 or HMP45) at heights of 4.5, 5.5, 7.0, and 9.0 m on the tower. Rn was measured by a ventilated radiometer (EKO, MR-50) at a height of 9.0 m. Soil temperatures were measured at 0.01 and 0.03 m underground by platinum resistance thermometers. The soil heat flux, $G_{-0.05}$ (Wm^{-2}), was measured by four soil heat flow meters (EKO, MF-180F) at 0.05 m underground. Recently, almost all researchers have used the eddy covariance method to determine CO_2 and water vapor fluxes, which was also performed at our observation site at a height of 9.0 m.

Extensive observations were conducted twice for this study, in addition to the routine observations. The first round was conducted from September 3-30, 2007, when the apple leaves had fully expanded and fruits were growing (hereafter called the growing period). The second was conducted from April 6-25, 2008, from when the snow cover had completely melted until two weeks after sprouting (hereafter called the sprouting period). Air temperatures and relative humidities (or dew-point temperatures) were measured by ventilated thermometer/hygrometers (HMP233 or HMP45, Vaisala) or by hand-made thermocouples at heights of 0.5, 1.5, 2.5, and 3.5m on the tower. Moreover, two apple trees with intermediate growth

near the tower were selected for trunk temperature measurement. Four thermocouples were buried for each tree at a depth of 0.02 m, at the north and south faces of the trunk at heights of 1 and 2 m.

All the measurements were conducted every 15 s, and the averaged data were recorded every 2 min by a data logger.

2.3 Calculation of HS

Since the eddy covariance method was performed at a height of 9.0 m, more than twice as high as the vegetation, we regarded the space below 9.0 m as “inside the canopy,” and HS was calculated for the space below 9.0 m every 30 min.

The sensible heat storage flux (HS_H : Wm^{-2}) and latent heat storage flux (HS_{LE} : Wm^{-2}) were calculated using the following formulae:

$$HS_H = \rho_a C_p (1.00\Delta T_{0.5} + 1.00\Delta T_{1.5} + 1.00\Delta T_{2.5} + 1.00\Delta T_{3.5} + 1.00\Delta T_{4.5} + 1.25\Delta T_{5.5} + 1.75\Delta T_{7.0} + 1.00\Delta T_{9.0})/1800 \quad (2)$$

$$HS_{LE} = \rho_a l (1.00\Delta q_{0.5} + 1.00\Delta q_{1.5} + 1.00\Delta q_{2.5} + 1.00\Delta q_{3.5} + 1.00\Delta q_{4.5} + 1.25\Delta q_{5.5} + 1.75\Delta q_{7.0} + 1.00\Delta q_{9.0})/1800 \quad (3)$$

where ρ_a is the air density (kg m^{-3}) determined depending on air temperature, C_p is the specific heat of the air ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), ΔT_i is the increment of the mean air temperature ($^\circ\text{C}$) over 30 min (1800 s) compared to that during the previous 30 min at a height of i m, l is the latent heat of the water vapor (J kg^{-1}), and Δq_i is the increment of the mean specific humidity (kg kg^{-1}) over 30 min compared to that during the previous 30 min at a height of i m. The coefficients of ΔT_i and Δq_i (1.00, 1.25, and 1.75) indicate the thickness (m) of the air layer as represented by each measurement. At layers below 4.5 m, the volume of air excluded by the tree was not taken into consideration, because it was estimated at less than 1% of the total volume.

Trunk heat storage flux (HS_T : Wm^{-2}) was calculated using this formula:

$$HS_T = W_T C_T \overline{\Delta T_T}/1800 \quad (4)$$

where W_T is the fresh weight of the trunk in the unit land area; the investigated value described in Section 2.1 (11.06 kg m^{-2}) was used for both growing and

sprouting periods. $\overline{\Delta T_T}$ is the increment of the mean temperature ($^\circ\text{C}$) at eight points on the trunk over 30 min compared to that during the previous 30 min. C_T is the specific heat of the trunk which was determined as follows according to Wada *et al.* (2002) and Miura *et al.* (2003):

$$C_T = (1 - m)C_D + mC_W + 335 \quad (5)$$

where m is the water content for the trunk, which was fixed as 0.52 in this study (although it slightly fluctuates throughout the year). C_W is the specific heat of water ($4,190 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), 335 is the correction term (Skaar, 1988). C_D is the specific heat of the dry wood ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), determined as follows depending on the mean temperature of the trunk ($\overline{T_T}$, $^\circ\text{C}$):

$$C_D = 1113 + 4.85\overline{T_T} \quad (6)$$

The leaf heat storage flux (HS_L : Wm^{-2}) was neglected for the sprouting period, while calculated for growing period using this formula:

$$HS_L = W_L C_L \Delta T_L/1800 \quad (7)$$

where W_L is the fresh weight of the leaf per unit land of area, namely 0.88 kg m^{-2} following the investigation described in Section 2.1. C_L is the specific heat of the leaf, calculated as $3,253 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$ because it contained 67% water ($4,190 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$) and the remaining 33% was mostly cellulose ($1,350 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$). ΔT_L is the increment of mean leaf temperature ($^\circ\text{C}$) over 30 min compared to that during the previous 30 min, but the air temperature in the canopy was substituted for leaf temperature because leaf temperature is difficult to measure accurately.

2.4 Calculation of G

G was calculated using the soil heat flux at a depth of 0.05m ($G_{-0.05}$) and the heat storage between 0.00 and 0.05m. Namely,

$$G = G_{-0.05} + C_{soil} (0.025\Delta T_{-0.01} + 0.025\Delta T_{-0.03})/1800 \quad (8)$$

where $\Delta T_{-0.01}$ and $\Delta T_{-0.03}$ ($^\circ\text{C}$) indicate the temperature changes of soils over 30 min at depths of 0.01 and 0.03 m, respectively. C_{soil} is the specific heat of the soil, regarded as $2.39 \times 10^6 \text{ J m}^{-3} \text{ } ^\circ\text{C}^{-1}$, although it fluctuates approximately $\pm 15\%$ depending on the soil water content. The coefficient of ΔT_i (0.025) indicates the thickness (m) of the soil layer as represented by each measurement.

3. Results and Discussion

3.1 Amount of each *HS* component and its diurnal change

In this study, the observed data were grouped into three categories based on the relative level of daily solar radiation (downward shortwave radiation). Observations were grouped as “solar radiation level 1” if the daily solar radiation was less than 35% of the potential solar radiation (Allen *et al.*, 1998; 2005); “solar radiation level 2” if the rate was between 35 and 70%; and “solar radiation level 3” if the rate exceeded 70%. The total observation days and the average amount of daily solar radiation for each group are shown in Table 1, while the diurnal change in mean solar radiation intensity for each category is illustrated in Fig. 1. Here, we can see that the mean solar radiation intensity fluctuated over time, and the diurnal solar radiation curves were asymmetric, especially in “level 1” and “level 2”. These irregular changes in solar radiation in “level 1” and “level 2” may trigger noises on the diurnal changing patterns of heat storage flux components.

Among the four heat storage flux components investigated, HS_T fluctuated most depending on the time of day. The diurnal change in HS_T is shown in Fig. 2. The diurnal change pattern was very similar through the season and solar radiation level. Namely, HS_T started to increase rapidly just before sunrise, peaking between 0700 and 0930 (JST), before decreasing and becoming negative around 1400, and bottoming out around 1800. Thereafter, it increased again, remaining negative until just before sunrise the following day. This diurnal change agreed very well with observations made in a larch forest in Hokkaido (Miura *et al.*, 2003). However, if the trunk diameter is larger, the timing of the peak or lowest point will be delayed since the thermal conductivity of the trunk is thought to be less. In fact, HS_T was reported to peak after 1200 in a temperate deciduous forest in the United

States (Oliphant *et al.*, 2004) and a tropical rainforest (Michiles and Gielow, 2008).

The range of diurnal fluctuation (difference between the daily maximum and minimum) was larger in the sprouting period than in the growing period, and at higher solar radiation levels. It reached as much as 52 Wm^{-2} in the sprouting period at solar radiation level 3. In the sprouting period, there are almost no leaves and thus the trunk easily receives solar radiation, and this condition probably resulted in the large diurnal fluctuation in HS_T . The range of diurnal fluctuation for HS_T as observed in this study was almost the same or even greater than those observed in various forests (Migliavacca *et al.*, 2009; Michiles and Gielow, 2008; Oliphant *et al.*, 2004), although the amount of trunk biomass ($11.06 \text{ kg FW m}^{-2}$) was smaller than those of forests (e.g. $43.79 \text{ kg FW m}^{-2}$ as reported by Michiles and Gielow). However, the 28 year old apple trees in this study had thick trunks with an average basal area of $32 \text{ m}^2 \text{ ha}^{-1}$ (unpublished data), which was almost comparable to forest canopies. Moreover, the branch pruning conducted every year in the apple orchard may have resulted in good light penetration into the trunks. These conditions—large basal area and frequent branch pruning—may explain the large HS_T fluctuation in the apple orchard of this study.

The heat storage component that showed the second largest diurnal fluctuation range was HS_H . As shown in Fig. 3, the diurnal pattern of change in HS_H was very similar to HS_T , and also agreed well with those obtained in forest canopies (e.g. Miura *et al.*, 2003). The diurnal range was larger for higher solar radiation levels, as was the case with HS_T , but with no conspicuous seasonal difference. This is probably because the experimental apple orchard was comparatively sparse and well ventilated, even during the growing period. The diurnal range of fluctuation was 16 Wm^{-2} at maximum for solar radiation level 3. Although the range was larger than that obtained in a larch forest in Hokkaido (Miura *et al.*, 2003), it was still far below those in a 20 m tall

Table 1. Number of observed days and daily mean solar radiation for each solar radiation level.

Solar radiation level	Growing period		Sprouting period	
	No. of observed days	Mean solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)	No. of observed days	Mean solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
1	8	5.19	4	6.63
2	5	9.89	3	14.37
3	15	18.20	9	21.56

Fig. 1. Diurnal changes in averaged solar radiation intensity for each solar radiation level. Vertical bars indicate standard deviations.

Fig. 2. Diurnal changes in trunk heat storage flux under various levels of solar radiation. Vertical bars indicate standard deviations at the times of diurnal maximum.

temperate deciduous forest (Oliphant *et al.*, 2004) or a tropical rainforest (Ohkubo *et al.*, 2006; Michiles and Gielow, 2008) where the sensible heat storage flux reached 30 to 100 W m^{-2} , becoming the primary heat storage component of the canopy. Thus, in the apple orchard, we can conclude that the most important heat storage term is HS_T , and that HS_H is generally not as important as in forests.

Fig. 3. Diurnal changes in sensible heat storage flux under various levels of solar radiation. Vertical bars indicate standard deviations at the times of diurnal maximum.

Fig. 4. Diurnal changes in latent heat storage flux under various levels of solar radiation. Vertical bars indicate standard deviations at the times of diurnal maximum.

The diurnal change in HS_{IE} is shown in Fig. 4. The flux tended to become large between 0700 and 0930, as was the case with HS_T and HS_H . However, the diurnal change, seasonal difference, and the difference among the solar radiation levels remained unclear. The fluctuation of HS_{IE} was small, ranging between -5 to 5 W m^{-2} , but with occasional exceptional observations. According to McCaughey and Saxton (1988), HS_{IE} increasingly fluctuates at times of rainfall, becoming the primary heat storage component. Michiles and Gielow (2008) observed an extremely low HS (below

Fig. 5. Diurnal changes in leaf heat storage flux in the growing period under various levels of solar radiation. Vertical bars indicate standard deviations at the times of diurnal maximum.

Fig. 6. Diurnal changes in total heat storage flux under various levels of solar radiation. Vertical bars indicate standard deviations at the times of diurnal maximum.

-200 W m^{-2}) at the time of rainfall in a tropical rainforest canopy. In our observations, HS_{IE} fell below -20 W m^{-2} three times, all of which occurred during or just after rainfall (data not shown).

The diurnal change in HS_L in the growing period is shown in Fig. 5. HS_L remained almost constantly within the range of $\pm 2 \text{ W m}^{-2}$, and was the smallest of the four heat storage components. Therefore, HS_L seemed negligible for flux observation in an apple orchard.

Finally, HS was calculated by summing up the four heat storage flux components; its diurnal change is

shown in Fig. 6. HS showed diurnal changes similar to those in HS_T , which was the largest contributing component. The diurnal flux fluctuation range was larger in the sprouting period, probably due to better light penetration into the trunk, and at higher solar radiation levels. At solar radiation level 3, the range of diurnal fluctuation reached 66 W m^{-2} for the sprouting period, as opposed to 44 W m^{-2} for the growing period. However, during the growing period, photosynthetic heat storage had to be taken into account, in addition to the four heat storage flux components. Preliminary analysis of the CO_2 flux at our site revealed that averages of 23 and $9 \text{ g m}^{-2} \text{ CO}_2$ were absorbed and evolved during daytime and nighttime, respectively, in June 2008 (Ito *et al.*, 2009). These corresponded to photosynthetic heat storages of 5 and -2 W m^{-2} , respectively. Therefore, the range of diurnal fluctuation for HS in the growing period may exceed 50 W m^{-2} if the photosynthetic heat storage is taken into account.

Since HS_T contributed most to HS , the trunk biomass will probably play an important role in determining HS in an apple orchard. The trunk fresh weight was 11.06 kg m^{-2} in our experimental site, but it fluctuates drastically depending on the tree age and rootstock. For example, Fukuda and Takishita (1993) reported that it was 2.95 kg m^{-2} for 16 year old apple trees grafted on invigorating rootstocks, as opposed to 1.44 kg m^{-2} for 10 year old apple trees grafted on dwarf rootstocks. Therefore, it must be noted that the results of this study cannot be adapted directly to other apple orchards.

3.2 The impact of HS on flux observation

In the Bowen ratio-energy budget method, H , IE and CO_2 fluxes are proportional to $(Rn - G - HS)$. To evaluate the error that will arise by neglecting HS and substituting $(Rn - G - HS)$ for $(Rn - G)$, we examined the value $(Rn - G)/(Rn - G - HS)$ every 30 min of the day, including both periods and every solar radiation level (Fig. 7). The results suggest that fluxes will be overestimated except for an hour just before sunrise (0500 to 0600) and for three hours in the afternoon (1330 to 1630), and that severe overestimations exceeding 20% will occur just after sunrise and just after sunset. Next, we separated daytime (0600 to 1800) and nighttime (1800 to 0600) data and performed regression analysis of $(Rn - G)$ against $(Rn - G - HS)$. As shown in Fig. 8, very close relationships existed and the following two regression equations were obtained. For daytime data:

$$Rn - G = 1.03(Rn - G - HS) \quad (9)$$

Fig. 7. Diurnal changes in the ratio $(Rn-G)/(Rn-G-HS)$ throughout the observations. Vertical bars indicate standard deviations.

Fig. 8. Relationships between $(Rn-G-HS)$ and $(Rn-G)$ for daytime and nighttime throughout the observations.

For nighttime data:

$$Rn - G = 1.16(Rn - G - HS) \quad (10)$$

From equations (9) and (10), we can suggest that overestimations of about 3 and 16% will occur in daytime and nighttime respectively, by neglecting HS in the Bowen ratio-energy budget method. This suggestion is also true for the energy closure ratio, $(H+IE)/(Rn-G-HS)$, in the eddy covariance method, because we can easily derive the following equations from equations (9) and (10).

$$\begin{aligned} (H + IE)/(Rn - G - HS) \\ = 1.03(H + IE)/(Rn - G) \end{aligned} \quad (9)$$

$$\begin{aligned} (H + IE)/(Rn - G - HS) \\ = 1.16(H + IE)/(Rn - G) \end{aligned} \quad (10)$$

In other words, we can expect the energy closure ratio to increase by 1.03 and 1.16 times in daytime and nighttime respectively, by taking HS into account, and this increase is generally thought to improve the energy imbalance of the observation site.

3.3 Estimation of HS

It has been reported that HS_T or HS_H can be estimated reasonably well from the change in the air temperature above the canopy (McCaughey and Saxton, 1988; Wada *et al.*, 2002; Michiles and Gielow, 2008). Because HS_T and HS_H were the first and second most important components of HS in this study respectively, we compared HS and the hourly change (from 30 minutes before to 30 minutes after) in the air temperature above the canopy (at 9.0 m). As illustrated in Fig. 9 for the growing period, the two values showed quite similar diurnal trends. However, they seemed to be slightly out of phase: the peak of HS often appeared 30 min after that of the temperature change. Such phase shift was also reported by Michiles and Gielow (2008), probably

Fig. 9. Comparisons between the diurnal changes in total heat storage flux and air temperature change rate for growing period under various levels of solar radiation.

Fig. 10. Diurnal changes in total heat storage flux every 30 min expressed as the percentage of daily solar radiation under various levels of solar radiation.

Dashed and solid lines indicate the approximation for level 1 and for levels 2 and 3, respectively.

due to the thermal conductivity of the trunk. We thus conducted a regression analysis by shifting the phase of temperature change by 30 min, and obtained the following equation for the growing period:

$$HS = 9.81(T[0] - T[-1]) \quad (11)$$

and for the sprouting period,

$$HS = 13.15(T[0] - T[-1]) \quad (12)$$

where $T[0]$ and $T[-1]$ are air temperatures above the canopy at present and 1 hour before, respectively. The rates of contribution for equations (11) and (12) were 0.68 and 0.86, respectively, suggesting that HS will be successfully estimated using these equations. The coefficients in equations (11) and (12), 9.81 and 13.15, are likely to reflect the rate of solar radiation to which the surface of the trunk exposed. During the sprouting period, higher value of the coefficient is probably due to the better light penetration into the trunk, because almost no leaf exists. Accordingly, it might be possible to estimate HS in another period by adjusting this coefficient depending on LAI.

In Fig. 10, HS was accumulated every 30 min and expressed as a percentage of the daily total solar radiation. Regardless of the period and solar radiation level, a common pattern of diurnal changes existed in relative HS : it started to increase rapidly just before sunrise, peaked between 0730 and 0900, then decreased linearly, bottomed out around 1800, and thereafter increased slowly until the following sunrise. The maximum and minimum percentages of HS differed depending on the period and solar radiation level, but the difference remained small between solar radiation levels 2 and 3. It thus seemed possible to estimate HS every 30 min based on the daily total solar radiation alone, by multiplying it with the percentage defined by the visually fitted dashed line (solar radiation level 1) or the solid line (solar radiation levels 2 and 3) shown in Fig. 10.

Figure 11 shows the relationship between the estimated and measured HS every 30 min. Estimation was conducted based on the temperature change above the canopy using equations (11) and (12) (Fig. 11A), or from the daily total solar radiation using the dashed and solid lines in Fig. 10 (Fig. 11B). The root mean square

Fig. 11. Relationship between measured and estimated heat storage fluxes every 30 min. Estimation was conducted from (A) temperature change rate, or (B) percentage of daily solar radiation.

errors (RMSEs) were 7.2 Wm^{-2} when estimated from the temperature change, and 9.7 Wm^{-2} when estimated from the solar radiation. The estimation from the solar radiation, although convenient because it uses only one datum per day, was often unsuccessful when large fluxes exceeding 40 Wm^{-2} or below -40 Wm^{-2} were observed. At almost all the flux observation sites, the temperature observation is conducted above the canopy, hence temperature change data is available. Therefore, it seems more practical to derive the estimation of HS from the temperature change above the canopy.

4. Conclusion

Our observations revealed that the maximum contribution term in the canopy heat storage in the apple orchard was HS_T , followed by HS_H and HS_{IE} , while HS_L was negligible. The diurnal fluctuation range of HS was larger in the sprouting period than in the growing period, and on days of higher solar radiation. By taking HS into account, the energy closure ratio for the eddy covariance method increased by 1.03 and 1.16 times in daytime and nighttime, respectively, and this increase was generally thought to improve the energy imbalance. HS could be estimated reasonably well (RMSE 7 Wm^{-2}) using the air temperature data above the canopy.

Acknowledgment

This study was supported by a Grant-in-Aid for Scientific Research (C, 19580291).

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