E-3.1 Quantification of micro-meteorological processes in tropical forest

Contact person TANI Makoto
Laboratory Chief, Forest Meteorology
Forestry and Forest Products Research Institute
Ministry of Agriculture, Forestry and Fisheries
P.O. Box 16, Tsukuba Norin Kenkyu Danchi-Nai, Ibaraki 305 Japan
Phone +81-298-73-3211, Facsimile +81-298-73-1542
E-mail tani3@ffpri.affrc.go.jp

Research staffs
TANI Makoto, OHTANI Yoshikazu, OKANO Michiaki, YAMANOI Katsumi
WATANABE Tsutomu, NOGUCHI Shoji and SAMMORI Toshiaki
(Forestry and Forest products Research Institute)
FURUKAWA Akio, KACHI Naoki*
(National Institute of Environmental Studies)
(* Present address: Tokyo Metropolitan University)
Abdul Rahim Nik, Zulkifli Yusop, Baharuddin Kasran, Saifuddin Sulaiman
CHAN Hung Tuck, YAP Son Kheong
(Forest Research Institute of Malaysia)
Muhammad Awang, Ahmad Makmom Abdullah
(Universiti Pertanian Malaysia)

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Abstract

Micro-meteorology and exchange processes of energy, water and carbon dioxide between a tropical rain forest and the atmosphere were monitored in Pasoh Forest Reserve in Peninsular Malaysia. The meteorological monitoring gave essential information on vertical distributions of air temperature, vapor pressure and wind velocity within and above the forest canopy. Energy storage within a forest canopy was calculated from the distributions. Seasonal variation in albedo was obtained from the monitoring. Sensible and latent heat fluxes were estimated through Bowen ratio method. Almost all available energy was distributed to latent heat during wet conditions, but the ratio of latent heat to the available energy decreased in dry conditions. An eddy correlation observation was also conducted to measure the fluxes. Although the statistical structures of the wind component were not suitable for the calculation of the eddy correlation fluxes, the carbon dioxide flux above the forest canopy as well as the sensible and latent heat fluxes was estimated through the method.

Key words Tropical Forest, Micro-meteorology, Energy exchange, Eddy correlation method

1. Introduction

Understanding climatic effects of tropical rainforest at various scales requires observational studies on micrometeorological processes in and above the forest. However, findings from such observations are still limited especially in South-East Asia. In this study, we have conducted meteorological observation in a tropical rainforest of Peninsular Malaysia and have attempted to estimate fluxes of sensible heat, vapor and carbon dioxide between forest and atmosphere as well as distributions of meteorological factors in and above forest canopy.

The meteorological observation has been conducted in Pasoh Forest Reserve, Negri

Sembilan, Peninsular Malaysia. A 40 m observation tower was used for the observations, and a long term monitoring was continued more than one year. Because some of the tree crowns surrounding the tower had exceed the tower height, a 12 m extension of the tower was executed in January 1995. The position of continuous meteorological monitoring was moved from the height of 41 m to that of 52.6 m after the extension. Additional meteorological observations were conducted to estimate vertical distributions of meteorological factors and the fluxes above the forest. Some observation results are reported in this paper.

2. Experimental design

(1) General meteorological factors

An observation tower system was established in 1992, in an experimental forest of FRIM in Pasoh Forest Reserve, Negri Sembilan, Peninsular Malaysia (2° 59'N and 102° 18'E). Meteorological sensors were installed on the highest floor at 41 m high in April 1993. The micrometeorological monitoring has continued since then. The monitoring factors are downward and upward solar radiation, net radiation (downward and upward budget of multi-wave radiation), wind direction and velocity, dry and wet bulb temperatures and rainfall. Heat flux was monitored at 2 cm deep under the forest floor (Tani and Abdul Rahim, 1995).

After the extension of the tower, these sensors except for those installed under the ground have been moved from 41 m to 52.6 m high. In addition, observations necessary for estimating vertical distributions of some meteorological factors and fluxes above the canopy were conducted, using the extended tower.

The distributions of air temperature, vapor pressure and wind velocity were also estimated in a short period, from 4 to 5 of March, 1995, by the ventilated psychrometers and anemometers set at the 6 heights (52.6, 49.1, 41.5, 33.0, 17.0, 1.0 m) between the ground and the tower top.

(2) Bowen ratio method

Ventilated psychrometers have been installed at the two height (52.6 and 43.6 m) above the canopy to estimate heat and vapor fluxes by means of Bowen ratio method. The method is outlined as follows. The energy balance above the forest canopy can be written as

$$Rn = S + lE + Qs + A \qquad (1)$$

where Rn is the net radiation, S is the sensible heat flux, lE is the latent heat flux for evapotranspiration, Qs is the energy storage within a canopy, the estimation process of which will be explained in the next section, and A is the net rate of energy absorption by photosynthesis and respiration. A is usually negligible. Then,

$$Rn = S + lE + Qs \qquad (2)$$

The Bowen ratio B is introduced as

$$B = S / lE \qquad (3)$$

B is calculated from the air temperatures, T1 and T2, and the vapor pressures, e1 and e2, measured at two heights within surface boundary layer above the canopy based on the assumption of the equality of the eddy exchange coefficients for sensible heat and vapor.

Therefore,

$$B = (Cp\ P / 0.622)\ (T1 - T2) / (e1 - e2) \qquad (4)$$

where Cp is the specific heat at constant pressure, P is the air pressure. S and lE can be given through Eqs. (5) and (6) from the value of B as

$$S = B\ (Rn - Qs) / (1 + B) \qquad (5)$$
$$lE = (Rn - Qs) / (1 + B) \qquad (6)$$

Thus, the air temperature and vapor pressure values measured at 52.6 m and 43.6 m can give the both fluxes.

(3) Energy storage within forest canopy

The total flux of energy storage within a forest canopy can be written as

$$Qs = Qa + Qw + Qv + Qg \qquad (7)$$

where Qa, Qw, Qv and Qg are sensible, latent, biomass and soil heat storages. Qa, Qw and Qv are calculated by the observed air temperature and humidity data within the forest. Qg is assumed to be neglected, because the rate of Qg to Rn is approximately 1% while in a day time by the result of the observation.

An application of Bowen ratio method requires an easy estimation of Qs from the routine monitoring on dry and wet bulb temperatures at the tower top (52.6 m). A paramerization for each of Qa, Qw and Qv is attempted based on their estimation results.

(4) Turbulent fluxes

Turbulent fluxes of sensible, latent and carbon dioxide were measured at the height of 52 m of the tower from 21 to 28 of March in 1995, using a 3-dimensional ultrasonic anemometer-thermometer and an infrared H_2O/CO_2 fluctuation meter. Data were recorded at the sampling frequency of 10 Hz (every 0.1 s). At the same height, the average values of air temperature, humidity and average CO_2 concentration were measured with a ventilated psychrometer and an NDIR, respectively.

The eddy correlation method was used for the computation of sensible, latent heat and CO_2 fluxes. A procedural coordinate's transformation for three dimensional components of wind velocity (Kaimal, 1988) and a correction for the thermal component (Kaimal and Gaynor, 1991) was applied to the data. The mean and the perturbation part of the fluctuation data of scalars were separated using a recursive digital low-pass filter (McMillen, 1987). The Webb's correction (Webb et al. 1980) also was taken into account.

As mentioned later, the computed sensible and latent heat fluxes were apparently small. The turbulent fluxes were altered by the following procedure.

The Bowen ratio based on the eddy correlation fluxes is introduced as

$$B_{HW} = H / lE = (Cp / l)\ (\overline{w'T'} / \overline{w'q'}) \qquad (8)$$

where Cp is the specific heat of air at a constant pressure and l is the latent heat of water vaporization. Valuables $\overline{w'T'}$ and $\overline{w'q'}$ are directly calculated from the observed data by the ordinary procedure of eddy correlation method. Then the altered sensible (H^*) and latent heat (lE^*) fluxes can be given as

$$H^* = B_{HW} (Rn - Qs) / (1 + B_{HW}) \quad (9)$$
$$lE^* = (Rn - Qs) / (1 + B_{HW}) \quad (10)$$

Thus, the sensible and latent heat fluxes are obtained under the condition of closed energy budget.

The CO_2 flux according to the closed energy budget (Fc^*) is given in the same manner as

$$Fc^* = Fc\ lE^* / lE \quad (11)$$

where Fc is the raw CO_2 flux calculated by the ordinary procedure.

3. Results and discussion

(1) General meteorology and vertical distribution

Vertical distributions of air temperature (Fig. 1) show that temperature differences within canopy were small and it was getting low only near the forest floor in the daytime since the tropical rain forest is characterized by a complex and wide canopy. Vapor pressure decreased with the elevation and the latent heat seemed to be carried upward throughout a day (Fig. 2). Turning points were recognized at the elevation of 41.5 m for distributions of wind velocity during the neutral conditions (Fig. 3), and this suggested that the boundary layer was established above this elevation although the heights of emergent trees exceeded it.

The daily mean of albedo ranged from 0.125 to 0.139 and showed a seasonal change (Fig. 4). The albedo increased under the fine weather when the solar elevation was low but the effect of the elevation was not clear under the cloudy weather.

(2) Energy storage within a forest canopy

The sensible and latent heat storages can be calculated by changes in the air temperature and humidity at every time, respectively, within a forest canopy. The biomass heat storage was calculated by the heat conduction within the cylindrical tree stem, where the forest biomass was estimated by a tree diameter observation after Niiyama (unpublished data). The calculated daily changes of sensible, latent and biomass heat storages are shown in Fig. 5. The sensible heat was stored within the canopy air from sunrise to early afternoon, and latent heat was stored until early mid day. Owing to the small disturbance accompanied by a squall, both sensible and latent heat were stored and released repeatedly into and from the canopy after early afternoon. The daily change in biomass heat is similar to that in the sensible heat, but the former shows a gentle fluctuation with two hour delay compared to the latter.

The relationships of the sensible, latent and biomass heat storages within the canopy to the air temperature and humidity gradients in time at the tower top are shown in Figs. 6, 7 and 8, respectively. The experimental equations are given as Eqs. (12), (13) and (14) for the sensible, latent and biomass heat storages, with good linear correlations as backgrounds

$$Qa = 15.8(dT/dt) \quad Wm^{-2} \quad (12)$$
$$Qw = 21.5(de/dt) \quad Wm^{-2} \quad (13)$$
$$Qv = 11.6(dT/dt) \quad Wm^{-2} \quad (14)$$

where dT/dt and de/dt have dimensions (Kh^{-1}) and ($hPa\ h^{-1}$), respectively.

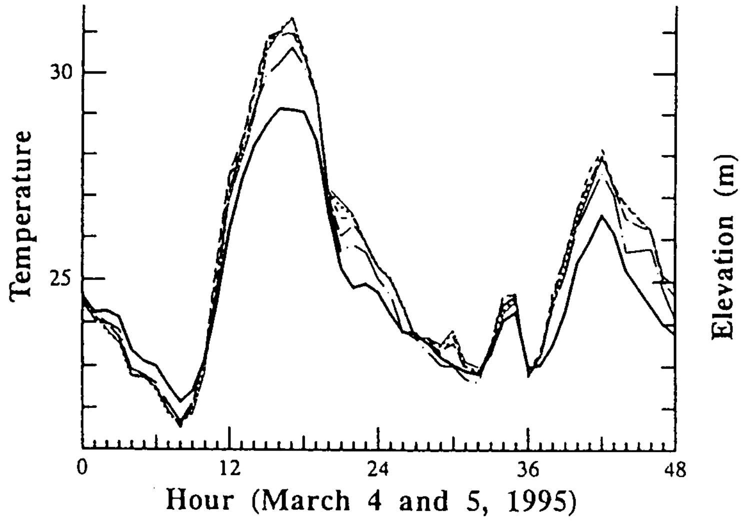

Fig. 1 Distribution of air temperature from 4 to 5 of March, 1995.
—— 52.6 m ‐···‐ 49.1 m ‐ ‐ ‐ ‐ 41.5 m — — —33.0 m —·— 17.0 m —— 1.0 m

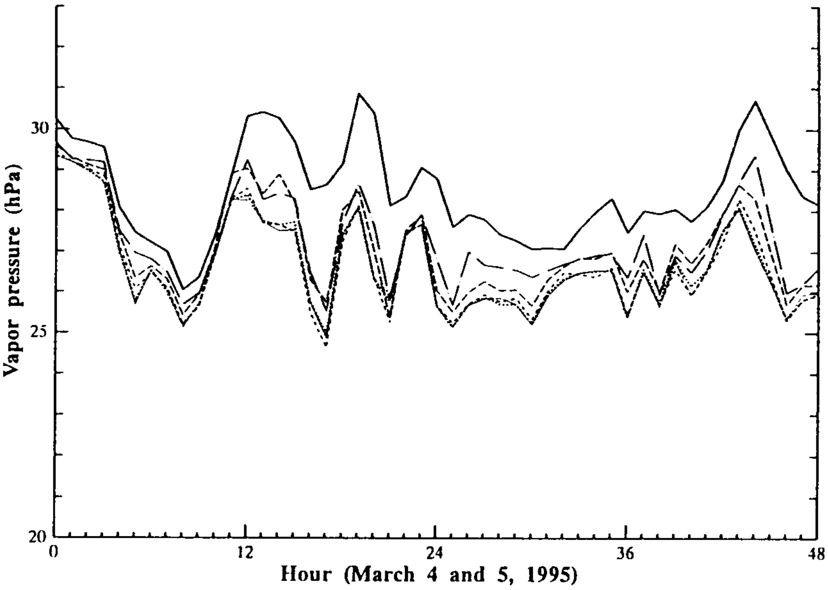

Fig. 2 Distribution of vapor pressure from 4 to 5 of March, 1995.
Symbols are the same as Fig. 1

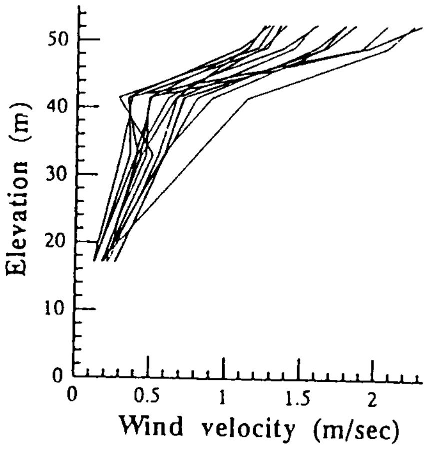

Fig. 3 Vertical profiles for wind velocity at the neutral condition.

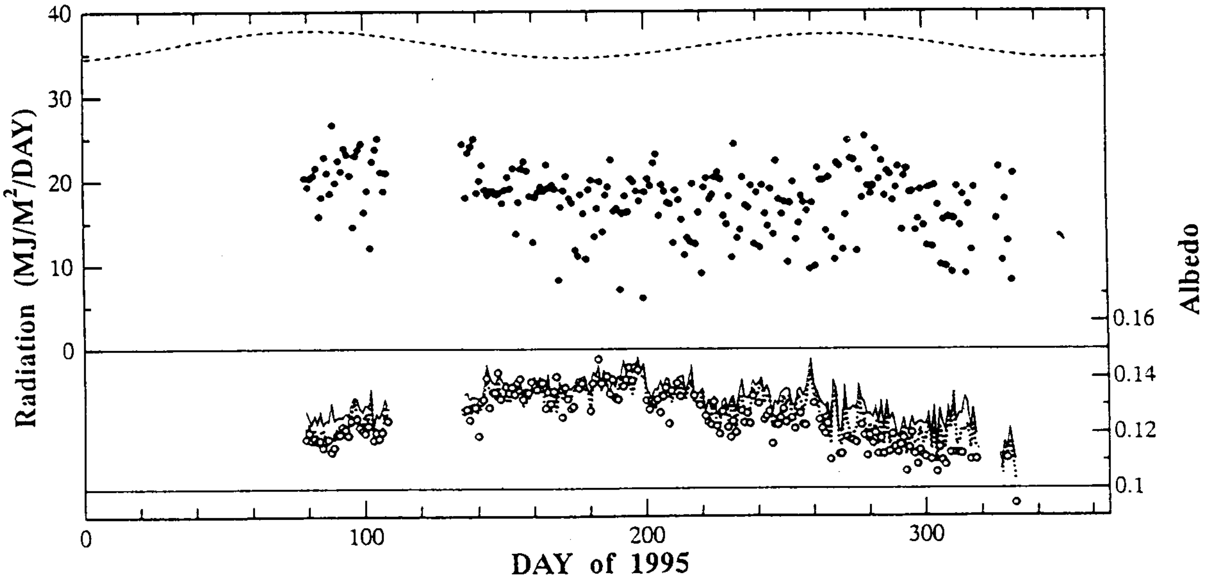

Fig. 4 Changes in daily values of downward solar radiation (•), solar radiation at the top of the atmosphere (– – –), albedo.

—— Daily mean albedo ··· Mean albedo from 1000 to 1600

o Mean albedo averaged from the records over 0.8 kW/m^2 from 1000 to 1600

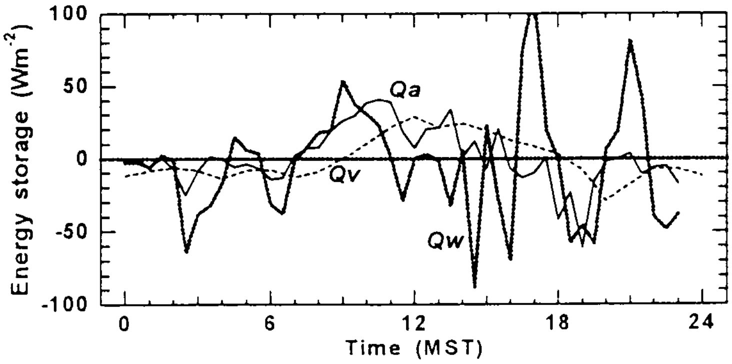

Fig. 5 Daily variations in sensible (Qa), latent (Qw) and biomass (Qv) heat storage.

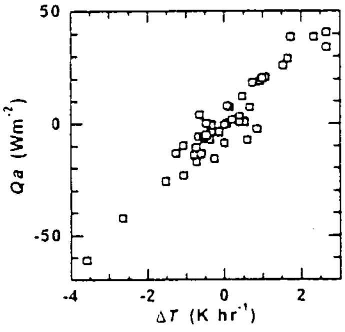

Fig. 6 Relation between temperature gradient in time above the canopy and the sensible heat storage within the canopy.

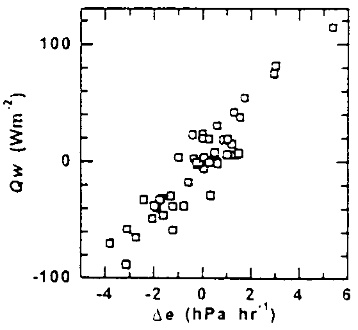

Fig. 7 Relation between water vapor gradient above the canopy and the latent heat storage within the cnopy.

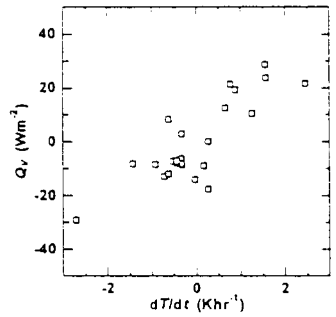

Fig. 8 Relation between temperature gradient in time above the canopy and the biomass heat storage witjin the canopy.

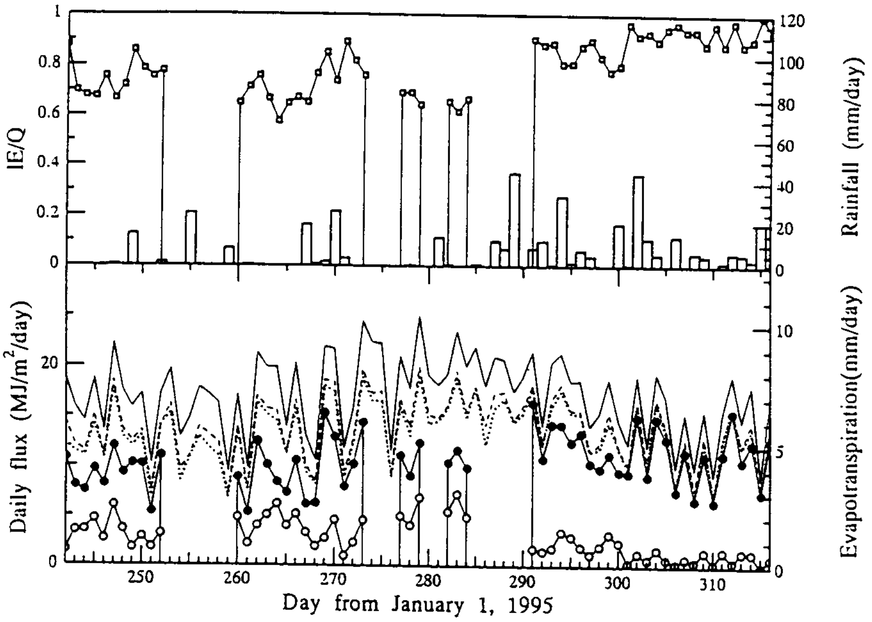

Fig. 9 Daily values of sensible (○) and latent heat (●) fluxes estimated by Bowen ratio method, downward solar radiation (——), net-radiation (- - -), available energy (Q=Rn−Qs)(·······), ratio of lE to Q (□), and rainfall (Bar).

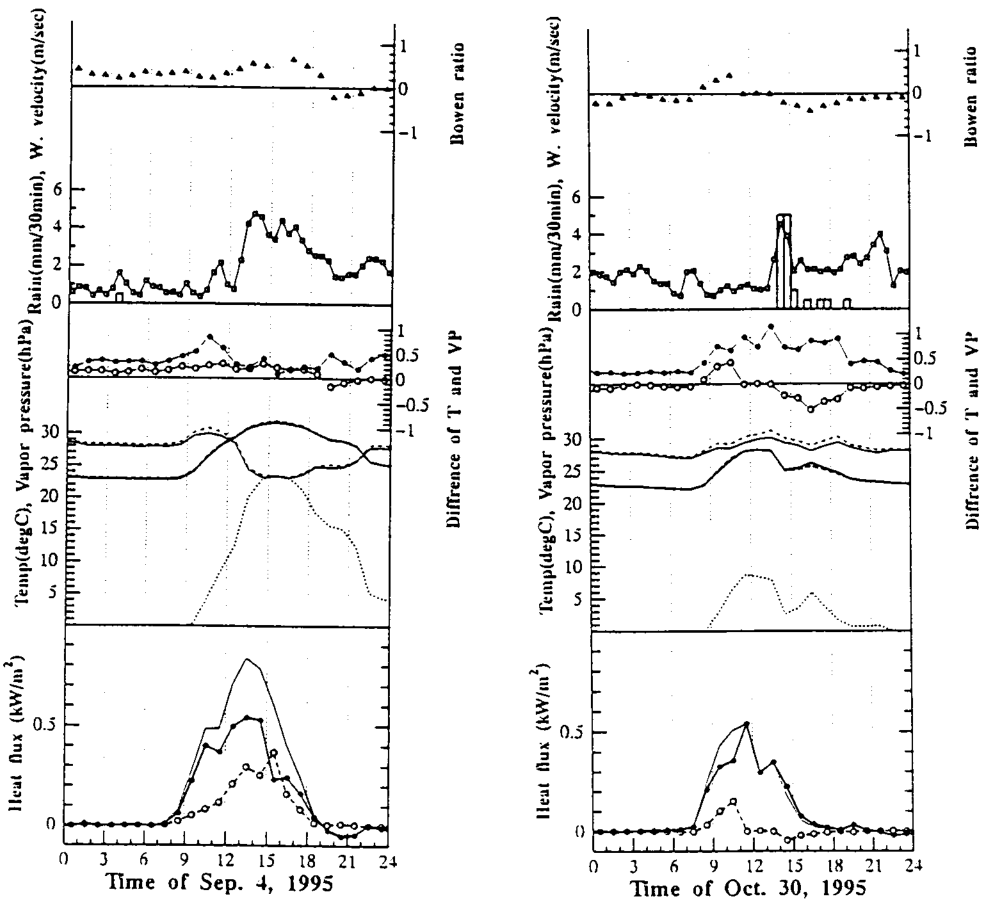

Fig. 10 Daily variations of heat exchange on 4/9/1995 (left) and 30/10/1995 (right).

▵ Bowen ratio □ Wind velocity Bar: rainfall

···· Vapor pressure deficit ○ Sensible heat ● Latent heat

—, --- Air temp. 52.6 and 43.6 m —, --- Vp. pressure at 52.6 m and 43.6 m

(3) Flux estimation by the Bowen method

The daily totals of heat fluxes, Rn−Qs(Q), S and lE calculated for the periods when the Rn had positive values are shown with the value of lE/Q and the daily total of rainfall in Fig. 9. Large percentages of Q were consumed as latent heat fluxes in the latter period in Fig. 9 since rainfall frequently occurred. This percentage decreased 60–70% when no rain days continued in the former period. Probably effects of soil wetness on transpiration may be involved in this percentage transition, but more data in dry conditions are required for further discussion.

Fig. 10 shows daily variations on 4/9/1995 and 30/10/1995 in air temperature, vapor pressure, vapor pressure deficit, rainfall and wind velocity at 52.6 m and differences in air temperature and vapor pressure between 43.6 m and 52.6 m as well as sensible and latent heat fluxes. Although the antecedent condition was dry, latent heat was larger than sensible heat. However, sensible heat became a little large in the afternoon on 4/9/1995. This may be caused by a function of stomata. On 30/10/1995, latent heat was very large due to the antecedent wet condition. Rain fell after 1400 and an air temperature inversion suggests that evaporation from the wet canopy occurred actively owing to the downward supply of sensible heat.

(4) Turbulent fluxes

The total flux consisted of both sensible and latent heats was only about 50% to the available energy (Fig. 11), and the eddy correlation fluxes for the sensible and latent heats ranged from 100 to 200 Wm^{-2} in the day time. The following reasons can be considered for the apparent insufficiency of energy fluxes: 1) mean wind velocity ranged 0.5 to 1.5 ms^{-1} throughout the observation except while the squall occurred, 2) the forest had a very complex canopy. Under the low wind speed conditions, it may be suggested that the wind field had unusual structures highly affected by the complex canopy. By the analysis, scalars sometimes had a high correlation to the lateral wind component rather than the vertical wind component, then the eddy correlation fluxes seemed to be decreased.

Even under the condition of the energy budget is not closed, it may be expected that the sensible, latent heats and carbon dioxide transferred by the similar mechanisms within a boundary layer. Thus, the altered sensible and latent heat fluxes under the condition of closed energy budget can be estimated using Eq.(9) through Eq.(11). The changes of heat fluxes in a day time are shown in Fig.12. In the same manner, the altered day time CO_2 flux is shown in Fig.13.

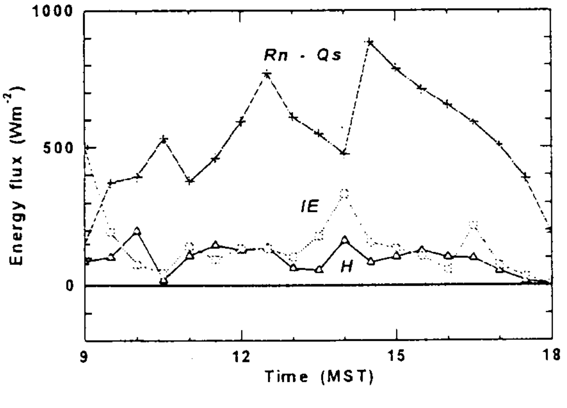

Fig. 11 Turbulent fluxes estimated by eddy correlation method.

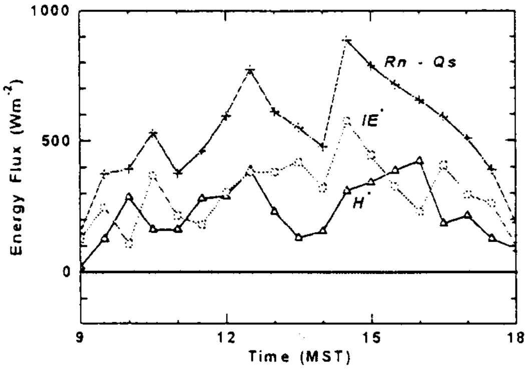

Fig. 12 Turbulent fluxes considering heat energy budget.

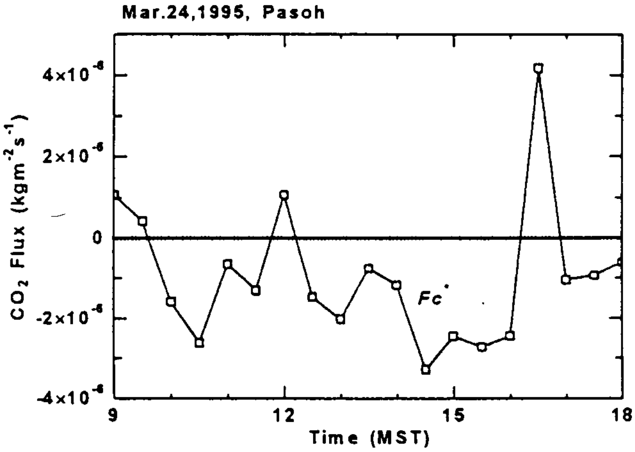

Fig. 13 Estimated CO_2 flux

The day time CO_2 flux was approximately $2x10^{-6}$ kg $m^{-2}s^{-1}$ toward to the forest, although the large uptake may be caused by the squall was observed in the late afternoon.

4. Concluding remarks

Meteorological observations for estimating micrometeorology and fluxes of energy, vapor and CO_2 were conducted in Pasoh Forest Reserve by using a 52.6 m tower. Since the forest had a complex and tall canopy, the estimation processes included some difficult points. However, the basic characteristics for those fluxes as well as micrometeorology have been gradually elucidated from our observations. Those seasonal variations, which mainly depends on rainfall in the climate of our tropical rainforest, will be estimated from our continuous observations in the study site.

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