梅雨および夏季におけるアカマツ林の熱収支･水収支

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Energy and Water Balance of a Pine Forest during a Bai-u and a Summer Season

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1. Introduction

It is important for understanding of the formation of climate in a small area to evaluate energy and water balance elements simultaneously (Yoshino, 1978). In most of the studies conducted in the forested area, however, energy balance and water balance have been measured separately. Therefore, main purpose of this study is to present the energy and water balance at the same time during a Bai-u[1] and a summer season and to discuss the results.

2. Method

2.1 Study Area

The observations were carried out at a pine forest in University of Tsukuba, 36°06′N, 140°06′E. The forest occupies the area of 1.9 ha and is composed mainly of Japanese Red Pine (*Pinus desiflora Sieb.* et Zucc.) with an average height of 10 m, average diameter breast high of 12.4 cm, and stand density of 27.0 trees per 100 m^2. Forest floor is partly covered with understory vegetation such as lacquer tree, Japanese Oak, etc.

2.2 Data Collection

Elements of energy balance were measured at the center of the forest by the following apparatus mounted on the tower. Net radiation (R_n) was measured with Funk type net radiometers (Eko Instruments Trading Co., Ltd., type CN-11) installed at heights of 1.5 m and 13.5 m above the ground surface. Sensible heat flux (H) was obtained through the eddy correlation method. Fluctuations of vertical wind speed and air temperature were measured with a sonic anemometer-thermometer (Kaijo Denki Co., Ltd., type DAT-100) and analyzed with a flux meter (Kaijo Denki Co., Ltd., type UDF-03). The sensor was set at a height of 13.5 m. Soil heat flux (G) was measured with a soil heat flux plate (Eko Instruments Trading Co., Ltd., type CN-9) buried at a depth of 1.0 cm. Dry- and wet-bulb temperatures were measured with handmade ventilated psychrometers using C-C thermocouple sensors (Kojima et al., 1983) at heights of 1.0, 5.0, 8.0, 10.0, and 13.5 m, and with ventilated psychrometers using P_t sensors (Iio Electric Co., Ltd., type SH-20) at heights of 0.5 and 2.0 m. Tree temperature was measured with C-C thermocouple sensor inserted into a tree trunk at a height of 4.5 m. Wind speed was measured with 3-cup anemometers (Makino Applied Instruments, type AC-750) installed at a height of 13.0 m. The outputs of each sensor were logged at sampling intervals of 5 sec and averaged in every 10 min and printed out by a data logger (Takeda Riken Industry Co., Ltd., type TR-2731).

Gross rainfall (P_g), throughfall (P_t), and stemflow (P_s) were measured after every rainfall event. P_g was measured with a tipping-bucket rain recorder installed at the open space. P_t was obtained as an average of the records of 50 pot-type rain gauges distributed in the rectangular plots (Majima and Tase, 1982). P_s was measured with stemflow samplers mounted on the stems of seven pine trees at a height of 1.2 m (Sugita, 1984). Soil water potentials were measured with tensiometers at a depth of 10 cm.

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2.3 Data Analyses

Intensive observation was carried out from July 12 to September 6, 1983. Collected data were analyzed on 10 min or one hour bases as follows. Evapotranspiration (ET) was obtained with the eddy correlation/energy balance method (Sugita and Kotoda, 1984): $lET=R_n-G-H-S$, where l is the latent heat of vaporization and S is the total energy flux to storage between ground level (Z_0) and reference level ($Z_r=13.5$ m). In this study, S was neglected for the calculation of hourly evapotranspiration. For 10-min values, however, S is evaluated from the changes in dry- and wet-bulb temperatures and tree temperature (Sugita and Kotoda, 1984): $S=S_a+S_q+S_f$, where S_a and S_q are the sensible and the latent heat fluxes to storage in air, respectively, and S_f is the sensible heat flux to storage in pine trees. Forest floor evaporation (E_f) is calculated on one hour basis with the Bowen ratio/energy balance method (Sugita and Kotoda, 1984): $lE_f=(R_n-G)/(1+\beta)$, where β is the Bowen ratio. Bowen ratio was obtained by the use of the data of air temperature and vapor pressure differences between 0.5 m and 2.0 m above the ground. The following quantities were evaluated as an average in a Bai-u and a summer season. Evaporation of intercepted water (E_i) or interception loss (I) can be evaluated as $P_g-P_t-P_s$, transpiration (T) as $ET-E_f-E_i$, and changes in subsurface water storage[2] (S_s) as P_g-ET.

3. Results and Discussion

3.1 Energy Balance

Fig. 1 shows the diurnal changes in energy balance elements on August 3, 1983. Net radiation was used mostly as latent and sensible heat fluxes in the daytime. Bowen ratio changed from about 0.3 in the early morning to the maximum value of 0.52 at noon and then became small rapidly to 0.03 in the late afternoon. Soil heat flux was small with $G/R_n=2-5\%$ for a whole day, which is coincident with the ratio of 1.2–4.9% (Hicks et al., 1975) and 3% (Kotoda, 1982). Ratio of S/R_n was usually 1–2%, but amounted to 10–20% for both 0500h–0600h and 1800h–1900h. Hence, the flux to storage may usually be negligible in the energy balance equation. Hicks et al. (1975) observed that the ratio of S/R_n for a pine forest was usually 1.2–7.2% and accounted for 118.3% at sunset and Stewart and Thom (1973) also confirmed that storage term became the same order of magnitude as R_n after sunrise and near sunset at a pine forest. Diurnal changes in three elements of a storage term S on the same day (Aug. 3) are shown in Fig. 2. Each element is expressed as cumulative values from zero at 0010h. Flux to storage in trees (S_f) had the largest diurnal range of the three and diurnal variation of S_f showed delay of phase compared with S_q and S_a. Fig. 3 shows the energy balance above the forest floor on Aug. 3. Because of the occur-

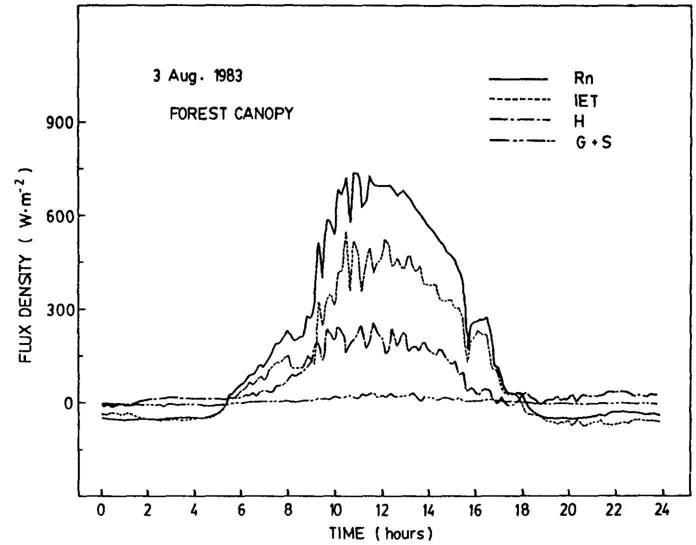

Fig. 1. Diurnal changes in energy balance elements above forest canopy.

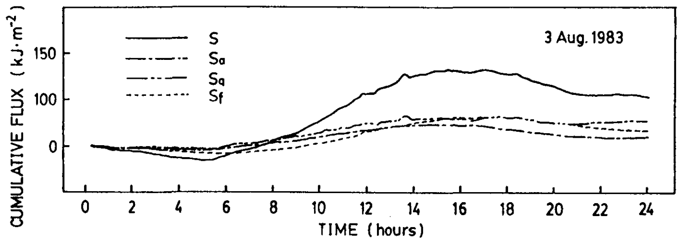

Fig. 2. Diurnal changes in energy fluxes to storage between reference level and ground surface.

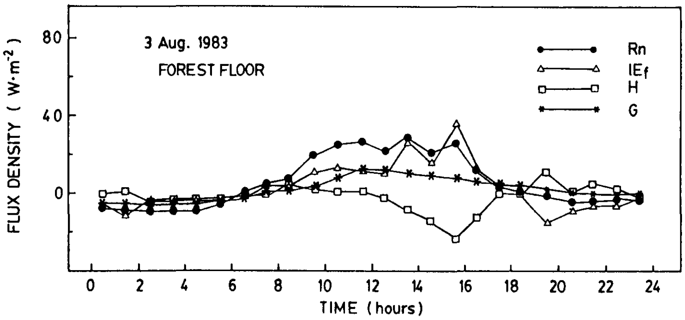

Fig. 3. Diurnal changes in energy balance elements above forest floor.

rence of downward sensible heat flux in the daytime, latent heat flux became greater than net radiation for 1500h–1600h.

Average values of the energy balance elements were calculated during the observation period. In the daytime (0600h–1800h) above the forest canopy, R_n was 232 $\mathrm{W \cdot m^{-2}}$, and was used as evapotranspiration (64%), sensible heat flux (34%), and soil heat flux (2%). In the nighttime (0000h–0600h, 1800h–2400h), energy was lost from the pine forest as net radiation (23 $\mathrm{W \cdot m^{-2}}$) and sensible heat flux (12 $\mathrm{W \cdot m^{-2}}$). To compensate for these energy losses, downward latent heat flux (34 $\mathrm{W \cdot m^{-2}}$) and upward soil heat flux (1 $\mathrm{W \cdot m^{-2}}$) took place. A mean Bowen ratio proved to be 0.53 for 0600h–1800h, when available energy ($R_n - G$) was positive, and –0.35 for both 0000h–0600h and 1800h–2400h. Daytime value may be comparable with the ratio of 0.0–1.5 for a Sitka Spruce (Milne, 1979), 0.49–0.84 for a Pine trees (Hicks et al., 1975), and 0.1 for Japanese Oak (Kotoda, 1982). Above the forest floor in the daytime, net radiation of 14 $\mathrm{W \cdot m^{-2}}$, which was about 6% of R_n above the forest canopy, and downward sensible heat flux of 1 $\mathrm{W \cdot m^{-2}}$ were the input of energy to the floor. Seventy percent of the energy input was used for evaporation from the forest floor and 30% entered into the soil.

3.2 Advection

One of the advection terms, or horizontal sensible heat flux (H_x) was estimated with a simple method. H_x may be expressed as

$$H_x = \rho_a C_p \int_{z_0}^{z_R} u \, \mathrm{d}T_a/\mathrm{d}x \, \mathrm{d}z \qquad (1)$$

where ρ_a is the density of air, C_p the specific heat of air at constant pressure, u the wind speed, and $\mathrm{d}T_a/\mathrm{d}x$ the horizontal gradient of air temperature. Observations of vertical wind profiles in this area showed that wind speed below the canopy was usually 5–30% of that just above the canopy. Therefore, advection proved to be most significant in the layer between 8.5 m and 13.5 m above the ground. Thus eq. (1) reduces to

$$H_x = \rho_a C_p \bar{u} \, 5.0 \, \overline{\mathrm{d}T_a/\mathrm{d}x} \qquad (2)$$

where overbars denote the mean values between 8.5 m and 13.5 m above the ground. Canopy temperature was measured with the infrared thermometer. It may be sufficient to use canopy temperature as T_a in eq. (2) for the approximate estimation of H_x, since vertical air temperature gradient above the canopy was kept less than 0.3°C·m^{-1} in this area even on a sunny day. Fig. 4 shows one of 20 isothermal maps of the forest canopy measured during the observation period. Table 1 shows the 10-min averaged energy balance above the forest canopy for four days selected so as to cover the various weather condition, although average wind speed greater than 2 m·s^{-1} scarcely occurred during the observation period. The values of H_x and H_x/R_n are also represented. H_x/R_n is the error in determination of energy available to sensible and latent heat fluxes expected in the case of neglecting H_x. These results confirmed that horizontal sensible heat flux was of the order of 10^0-10^1 W·m^{-2} at the observation point during a Bai-u and a summer season. As for the further discussion on advection term, however, direct measurements of horizontal gradients of air temperature and vapor pressure will be necessary, especially during a winter season when strong wind speed of monsoon is prevailing in Japan.

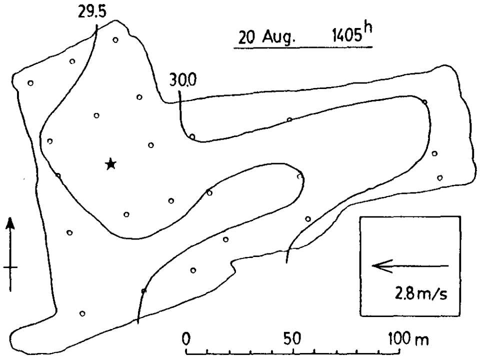

Fig. 4. Isothermal map of forest canopy. A lower right arrow and a numeral represent wind direction and wind speed, respectively. An asterisk and open circles denote observation tower and observation point, respectively.

3.3 Water Balance

Table 2 shows the water balance of the pine forest for both 12 days during a Bai-u season (July 12–24) and 42 days during a summer season (July 26–Sept. 6, except for Aug. 28). During observation periods, the maximum pF value was 2.2 at a depth of 10 cm, so that evapotranspiration wouldn't be suppressed by soil water shortage (Tajchman et al., 1979). In calculations of ET and E_f, upward latent heat flux was integrated for a day, as the observations showed scarce dewfall on pine tree leaves (Sugita, 1984). There may be large error in E_f calculation with energy balance method due to large scatter of R_n above the forest floor. Therefore, E_f values give only an indication of order of magnitude. Stålfelt (1963) and Rutter (1966) showed by a rough

Table 2 Water balance of pine forest. Figures in the parentheses represent a daily average of each flux.

	July 12–24 1983		July 26–Sep. 6 1983	
P_g	24.5	(1.9)	207.5	(8.6)
P_t	17.4	(1.3)	187.8	(7.8)
P_s	0.0	(0.0)	3.0	(0.1)
I	7.1	(0.5)	16.7	(0.7)
ET	35.2	(2.7)	140.5	(5.9)
T	25.4	(2.0)	116.1	(4.8)
E_i	7.1	(0.2)	16.7	(0.7)
E_f	2.7	(0.5)	7.7	(0.3)
S_s	−10.7	(−0.8)	67.0	(2.8)

Unit: mm (mm·d^{-1})

Table 1 Energy balance above forest canopy.

		20 Aug. 1405h	16 July 1620h	29 July 1110h	18 July 1530h
R_n	(W·m^{-2})	575	118	628	147
H	(W·m^{-2})	220	36	176	39
lE	(W·m^{-2})	350	78	439	101
U	(m·s^{-2})	2.8	2.4	1.5	1.0
dT_a/dx	(°C·m^{-1})	9.7×10^{-6}	1.4×10^{-5}	9.6×10^{-6}	9.5×10^{-6}
H_x	(W·m^{-2})	90	23	52	8
H_x/R_n	(%)	16	19	8	5

water balance method that E_f accounted for 10 to 12% of ET in various forests, which is the same order as the results of this study.

During a summer season, 43% of P_g was produced by a typhoon and the number of days with precipitation was only 9. On the contrary, during a Bai-u season, in spite of large number of days with precipitation, its amount was so small that large parts of precipitation were intercepted. It is thought that evapotranspiration became large with large interception percentages during a Bai-u season, because the evaporation rate of intercepted rainfall is about 30% faster than that of transpiration (Sugita, 1984).

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Note

1) Bai-u season is a rainy season prevailing in Japan and Middle China from early June through early or mid July.
2) Subsurface water storage is defined in this study as water stored under the ground surface.

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