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Spatial Variability of Soil Heat Fluxes in a Conifer Forest

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침엽수림에서 토양열 플럭스의 공간 변화

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ABSTRACT

The spatial variability of soil heat fluxes in a conifer forest was investigated by meteorological measurement. The maximum daily averages of Rs_{dn} and Rn were about 260 Wm^{-2} and 180 Wm^{-2}. The daily average of G was typically 10 % of net radiation during mid-July to mid-August. The measured soil heat flux of G_6 was suitable to calculate G within 2 % error during the study period. A time delay in the maximum flux at a depth of 0.1 m by heat storage was observed. About 10 to 15 Wm^{-2} of error can occur, if it is neglected.

Key words **: spatial variability, soil heat flux, heat storage, Net radiation**

I. INTRODUCTION

Soil is an important sink or source of energy. Measurements of soil-surface heat flux have uncertainties associated with spatial variability, particularly in forests (Kustas *et al.*, 2000). One of the main objectives of KoFlux is to analyze long-term fluxes and energy components of a forest area. All components (net radiation Rn, latent LE, sensible H, and soil G, heat fluxes) were measured accurately and independently from one another to look for energy budget closure. The equation of surface energy budget is as follows:

$$R_n - G = LE + H \qquad (1)$$

Soil heat flux was usually derived from measurements with soil heat flux plates and an added storage term (G_s) for storage in the layer between the soil surface and the soil heat flux plate (Oke, 1987). McCaughey (1988) indicated that the total soil heat storage could be up to 10% of net radiation on overcast days or immediately following rainfall. Mayocchi and Bristow (1995) reported that soil storage was sometimes as large as 80 Wm^{-2}. Reliable estimates of energy budget require an accurate estimation of soil heat flux. Its contribution can be significant over long periods of time, up to several months. In this study, temporal and spatial variability of soil heat fluxes, and the ratio of the net radiation to soil heat flux will be examined.

II. MATERIAL AND METHODS

2.1. General forest characteristics

Fluxes and micrometeorological measurements were continuously made above a coniferous forest in Kwangneung (37°45′25.37″ N, 127°9′11.62″ E, ~340 m

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m.s.l) near Seoul from mid-August 1998 to the present. Mean canopy heights were about 16 m. The main canopy was composed of *Pinus koraiensis*. A 31 m-tall tower was erected on low hills with varying slopes and a fetch over 2 km, depending on wind direction. Bulk density and porosity of the soil were about 0.83 (kg/m^{-3}) and 0.68 (kg/kg) near the measurement site. A more detailed description of the canopy architecture, species composition and soil properties is provided by the Korea Forest Research Institute (1994).

2.2. Instruments and data processing

Measurements of net radiation (CNR-1 Kipp and Zonen) were made from a height of 31 m. To measure spatial average of soil heat fluxes, six different locations around the tower were selected. Soil heat flux plates (G_1 to G_6, HFT, Campbell Science Inc., hereafter CSI) were buried at each location at 0.1 m under the surface. To avoid the underlying soil and therefore faster drying than that of the surrounding surface soil, the depth of 0.1 m was decided. The soil temperature probes (Ts_1 to Ts_6, TCAV, and CSI) were used to obtain the average soil temperature above each of the 0.1 m plates. Temperature probes were used to estimate the amount of energy stored in the layer above the heat flow transducer. Also, soil moisture was measured at two locations for three depths (0.1 m, 0~0.3 m, and 0.3~0.6 m) using water content reflectmeters (CS615, CSI). They were connected to a digital data-logger (CR23X, CSI), where data were collected every 30 second, and averaged over a half-hour period. To properly evaluate daily fluxes, it is desirable to maintain nearly continuous data records. Small gaps of missing data were filled via interpolation between earlier and later measurements. Larger data gaps were filled using the linear regression equation describing the data filling (see Section 3.1).

Surface soil heat flux (G) was calculated from the measured flux at depth 0.1 m (G_d, here $d=1$ to 6) plus the heat storage in the overlying soil,

$$G = G_d + \int_0^d \frac{\partial}{\partial t}(C_v T)\,dz \qquad (2)$$

where, $C_v=(\rho_v C_s)(1-\phi)+\rho_w C_w \theta$ (Garrat, 1992), ρ_v and ρ_w are the density of the soil and water, respectively. C_s and C_w are the specific heat of the soil and water, respectively. ϕ and θ are bulk density of the soil and volumetric soil water content of the soil. Bulk density was determined from several soil samplings. In this study, data from 20 July to 30 September 2001 were used.

III. RESULTS AND DISCUSSION

3.1. Data filling

To obtain daily or monthly sums it was necessary to fill in missing data. Missing soil heat fluxes were assessed from a regression equation. Soil heat fluxes measured at the depth of 0.1 m (G_d) from the surface were compared with the calculated soil heat flux (G). The measured soil heat fluxes of G_3, G_4, and G_5 were larger than 20% of G, but the measured soil heat flux of G_6 was less than 2% of calculated G. So the measured soil heat flux of G_6 could be used to calculate G within 2% error when other soil heat fluxes were not measured (Fig. 1).

$$G = 1.015\,G_6 + 0.445 \qquad (3)$$

3.2. Environment condition

Total precipitation was 1282 mm during January to November 2001. About 45% of precipitation (570 mm) occurred during the study period (Fig. 2). The soil water content of the top 0.1 m of soil is shown for the study period in Fig. 3. High summer rainfall (e.g., >120 mm/day) increased soil water content (SWC) up to about 30% during July to mid-August. Soil water content gradually declined due to the lack of precipitation after mid-August. Net radiation (Rn) was about 87% of downward short wave radiation (Rs_{dn}) during the study period by the one-to-one liner regression (not shown). Maximum daily averages of Rs_{dn} and Rn were about 260 Wm^{-2} and 180 Wm^{-2} during the study period, respectively (Fig. 4). After mid-August, the variation of Rs_{dn} and Rn declined. Net radiation was less than 60 Wm^{-2} on cloudy and rainy days during the study period.

3.3. Spatial variation

Fig. 5. shows variations of soil heat fluxes, measured at six different locations. Magnetite varied from -10 to 25 Wm^{-2} at all locations. Maximum soil heat flux was measured at location 4 (G_4), which was located in an open place. A time delay was observed in the maximum flux at a depth 0.1 m in Fig. 5. This means that heat storage in the soil layer above the soil heat probe must be included when measuring soil heat flux. If it is

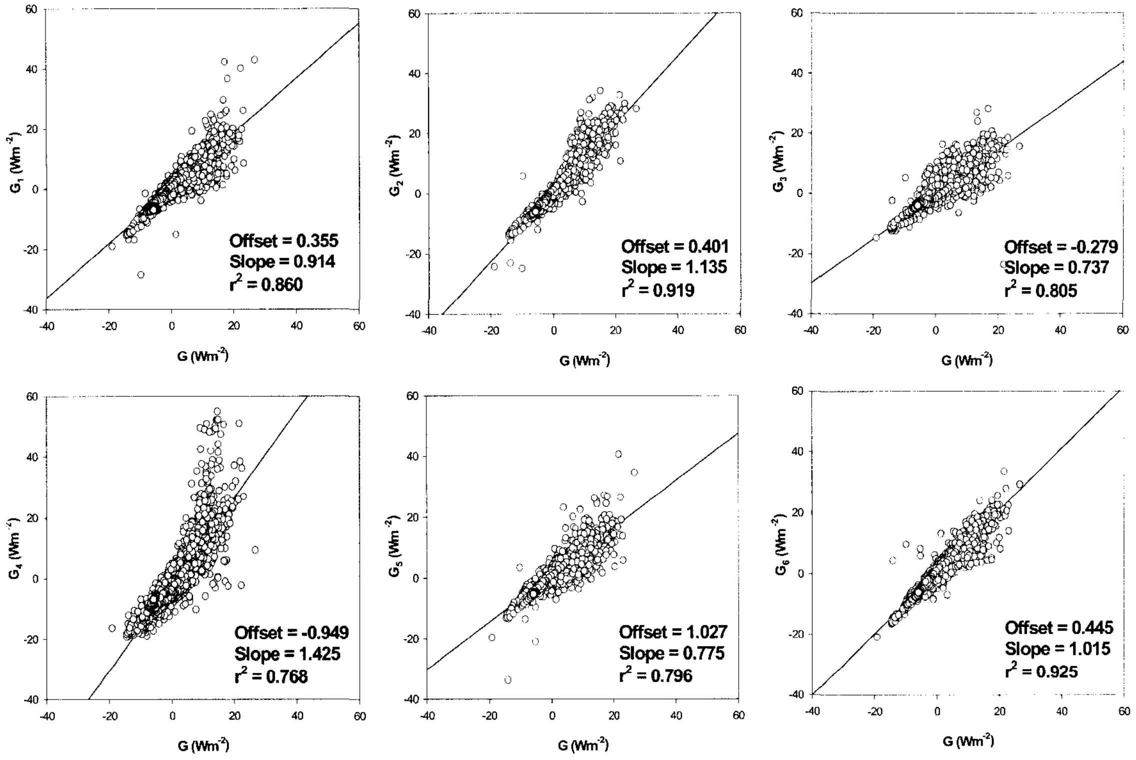

Fig. 1. Comparison of measured soil heat fluxes at under 0.1 m under the ground (G_1 to G_6) with calculated soil heat flux (G).

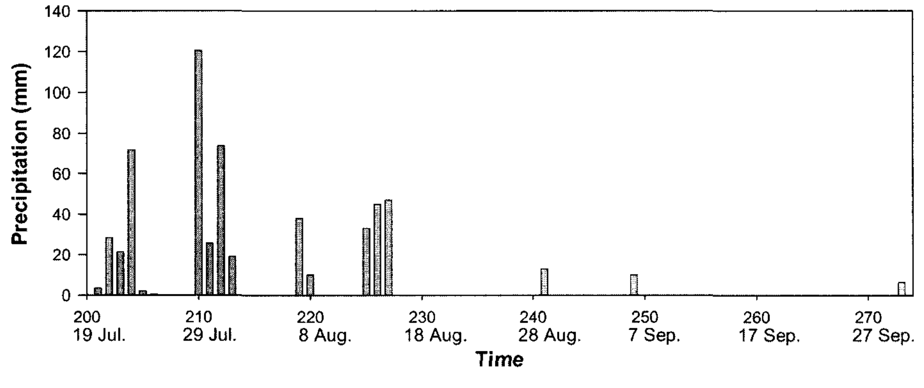

Fig. 2. Variation of precipitation during the study period.

neglected, about 10 to 15 Wm^{-2} error can occur.

Soil temperature and soil heat fluxes were measured at six different locations around the measurement site. Soil temperature and soil heat flux varied, respectively, from 20 to 25°C and -5 to 10 Wm^{-2} during mid-July to mid-August, then gradually decreased (Fig. 6). The maximum value difference was approximately 2°C. However, the difference was small during cloudy and rainy days in mid-August. Ts_d and G_d show similar variations during the study period. Especially during cloudy and rainy days of mid-August, Ts_d and G_d gradually decreased to 20°C and -5 Wm^{-2}. G_d remained at almost zero during mid-August to mid-September, and then the value changed to negative (Fig. 7).

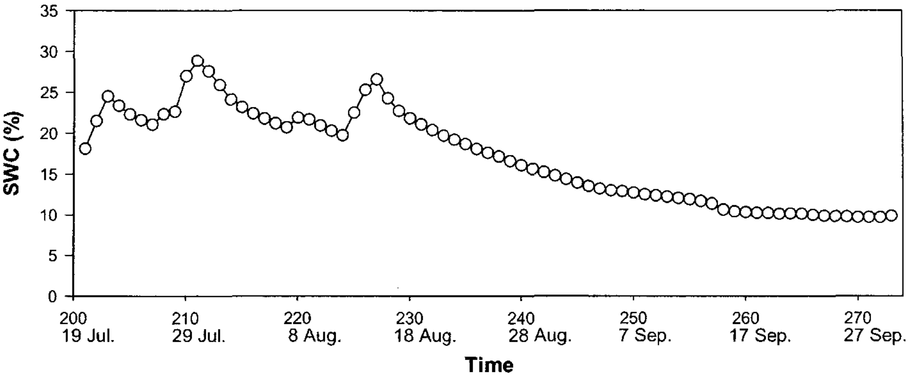

Fig. 3. Variations of soil water content (SWC) during the study period.

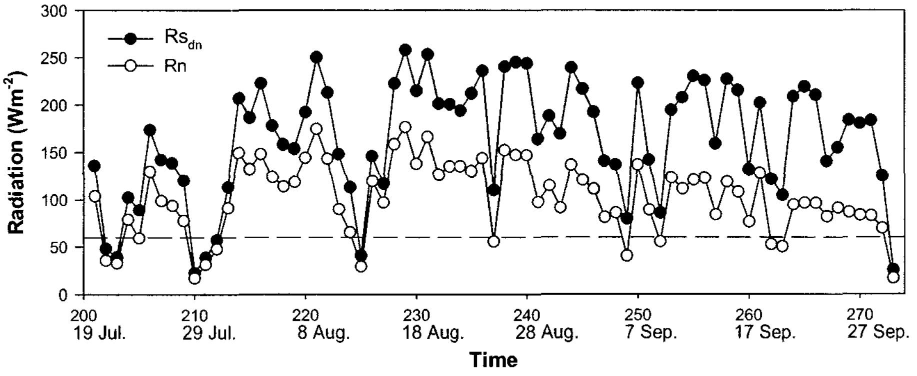

Fig. 4. Variations of the daily average downward short wave (Rs_{dn}) and net radiations (Rn) during the study period.

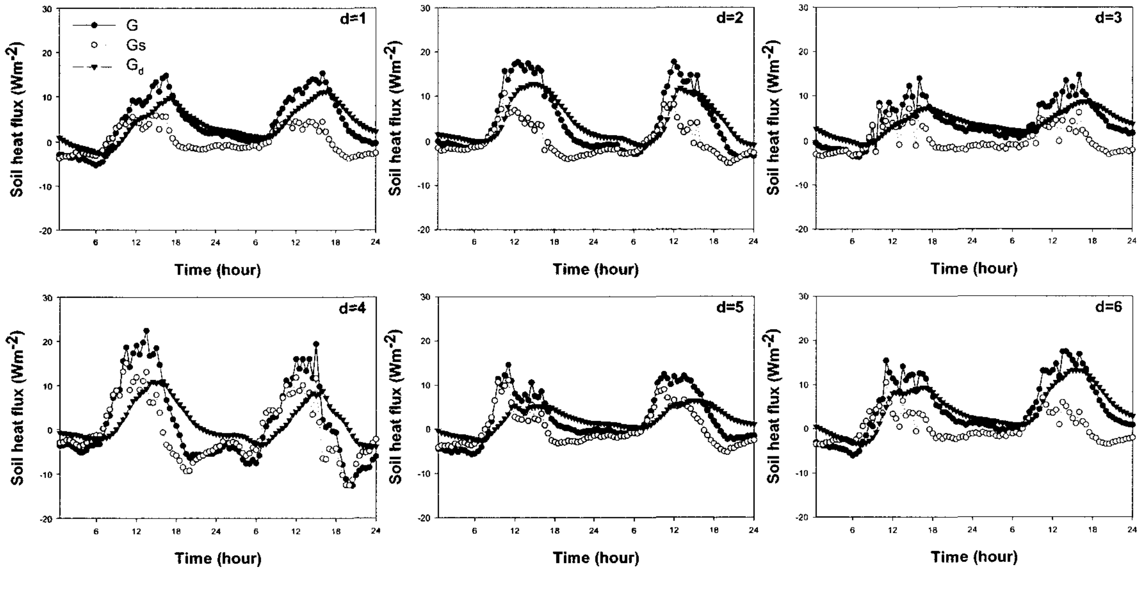

Fig. 5. Variations of soil heat fluxes at six different locations during 20 to 21 Aug. 2001.

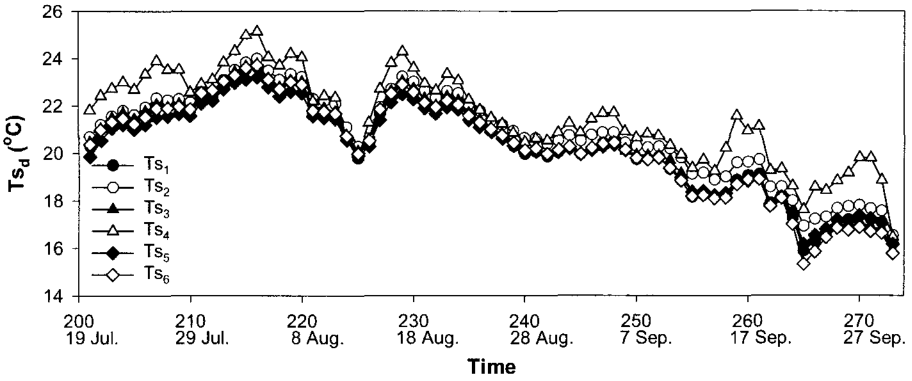

Fig. 6. Variations of daily average soil temperatures (Ts_d) during the study period. Where d is 1 to 6.

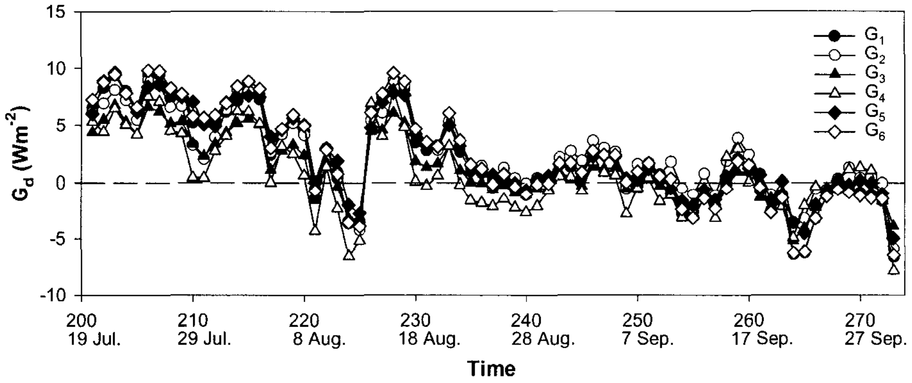

Fig. 7. Variations of daily average soil heat fluxes (G_d) during the study period. Where d is 1 to 6.

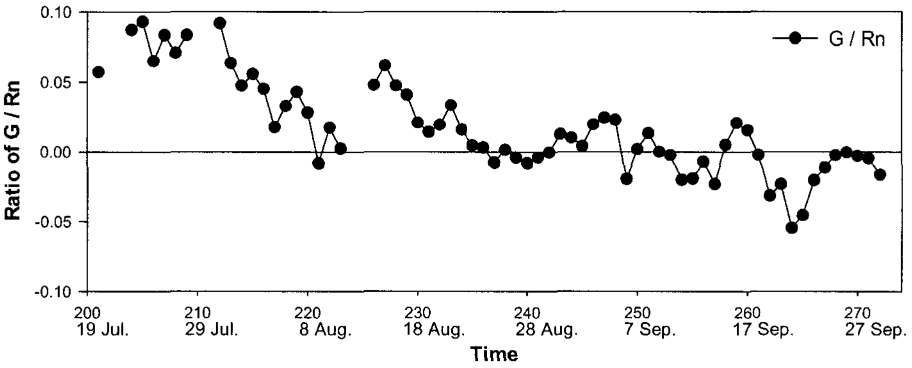

Fig. 8. Ratio of soil heat flux (G) and net radiation (Rn) during the study period.

The ratio of net radiation and soil heat flux was about 0.05 to 0.1 during mid-July to mid-August (Fig. 8). Soil served as an energy sink (G>0) until mid-September. The maximum daily average value was about 10 Wm^{-2}, about 10% of the net radiation during the study period. This value was similar to another study (Kustas *et al.*, 2000). Average midday rates were typically around 20 Wm^{-2} during the period. However, during late September, the soil heat flux reversed the sign and reached minimum daily average value (-10 W m^{-2}).

IV. SUMMARY AND DISCUSSION

In this study, temporal and spatial variations of soil temperatures and soil heat fluxes were discussed, as well as the ratio of the daily sum of soil heat flux and net radiation. We demonstrated the following:

- Measured soil heat flux of G_6 could be used to calculate G within 2% error.
- Maximum daily averages of Rs_{dn} and Rn were about 260 Wm^{-2} and a 180 Wm^{-2}, and net radiation was less then 60 Wm^{-2} on cloudy and rainy days.
- The maximum daily average value of G was about 10 Wm^{-2}, about 10% of net radiation during mid-July to mid-August.
- An error of 10 to 15 Wm^{-2} can occur, if soil heat storage is neglected.
- G_d remained at almost zero during mid-August to mid-September, and then the value changed to negative.
- Soil served as an energy sink (G>0) until mid-September, then changed to an energy source.

적 요

침엽수림에서 토양열 플럭스의 공간변화를 미기상 관측을 통해 조사하였다. 일평균 최대 하향단파복사 (Rs_{dn})와 순복사 (Rn)는 약 260 Wm^{-2}와 180 Wm^{-2} 였다. 7월 중순에서 8월 중순 사이의 일평균 토양열 플럭스는 대체로 순복사의 10 % 였다. 연구기간동안 측정된 토양열 플럭스 (G_6)와 계산된 토양열 플럭스 (G)와의 오차는 2 % 이내였다. 열 저류항에 의한 최대 플럭스의 지연이 관측되었다. 이러한 열 저류항을 고려하지 않을 경우, 약 10에서 15 Wm^{-2}의 오차가 발생할 수 있다.

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