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Seasonal changes in the net radiation/solar radiation ratio above a *Cryptomeria japonica* plantation forest

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I. Introduction

Predicting forest evapotranspiration has been a major goal in forest hydrology and ecology for many years (e.g., LANDSBERG and GOWER, 1997; KOMATSU and HOTTA, 2005).

Evapotranspiration is a major component of the forest water cycle (e.g., WILSON *et al.*, 2001; KUMAGAI *et al.*, 2004a,b). Furthermore, evapotranspiration relates strongly to canopy photosynthesis (e.g., BERBIGIER *et al.*, 2001), which is a major component of the forest carbon cycle (e.g., Van WIJK *et al.*, 2001). Thus, accurate prediction of evapotranspiration rates leads to accurate prediction of forest water and carbon cycles (e.g., MCMURTRIE *et al.*, 1990; HINGSTON *et al.*, 1998).

The Priestley-Taylor (PT) equation (PRIESTLEY and TAYLOR, 1972) is a useful tool to predict evapotranspiration rates from land surface. The PT equation formulates the evapotranspiration rate as

$$E = \alpha \frac{\Delta}{\Delta + \gamma} \frac{Rn - G}{\lambda}, \quad (1)$$

where E is the evapotranspiration rate, α is the PT coefficient, Δ is the slope of saturation vapor pressure function, γ is the psychrometer constant, Rn is the net radiation, G is the soil heat storage, and λ is the latent heat of water vaporization. Here, we define Rn and G for the daytime, which represents the period with positive solar radiation in this paper. Since evapotranspiration occurs actively during the daytime, the PT equation is often used with the input of daytime Rn and G rather than daily Rn and G (e.g., ARAIN *et al.*, 2003; KOMATSU, 2005).

For the following two reasons, the PT equation is highly applicable (KOMATSU *et al.*, 2005). First, the PT equation requires no wind speed data. This contrasts with the Penman-Monteith equation, which usually requires wind speed data to calculate aerodynamic conductance (e.g., CIENCIALA *et al.*, 1994a,b; STRASSER and MAUSER, 2001). Most historical meteorological station datasets and some regional datasets do not contain wind speed data (CAMPBELL and NORMAN, 1998). Second, the PT equation can be used with coarse time steps. The PT equation works with any time step (e.g., KUMAGAI *et al.*, 2004a,b; KOMATSU *et al.*, 2005) in contrast to the Penman-Monteith equation, which usually works in hourly time increments (e.g., CIENCIALA *et al.*, 1994a,b; KOMATSU, 2004). Most historical meteorological station datasets and some regional

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datasets do not include hourly data (CAMPBELL and NORMAN, 1998).

We need *Rn* estimates when calculating *E* based on the PT equation. The PT equation requires *Rn* and *G* data as input. However, *Rn* and *G* data are often unavailable from meteorological datasets (e.g., SEINO, 1993). *Rn* estimates are especially critical for calculating *E*, because *Rn* is much greater than *G* for most forest canopies (e.g., BARR *et al.*, 1994; BERNHOFER *et al.*, 1996).

Rn can be estimated from downward solar radiation $S^{\downarrow}$ assuming $Rn/S^{\downarrow}$ values (e.g., KUMAGAI *et al.*, 2004a, 2005; KOMATSU, 2005). *Rn* relates strongly to $S^{\downarrow}$ (JARVIS *et al.*, 1976; LANDSBERG and GOWER, 1997). JARVIS *et al.* (1976) summarized $Rn/S^{\downarrow}$ values observed above forest canopies in the growing season from earlier literatures. According to their summary, $Rn/S^{\downarrow}$ ranged from 0.7 to 0.9, and was typically 0.8. Thus, assuming $Rn = 0.8\ S^{\downarrow}$ may not cause large errors in *Rn* estimates during the growing season.

However, it is unclear whether constant $Rn/S^{\downarrow}$ values are applicable to *Rn* estimates in all seasons. To our knowledge, no studies have examined seasonal changes in $Rn/S^{\downarrow}$ values for forests. Earlier studies rarely used the PT equation to estimate evapotranspiration rates of forests, possibly because the theoretical background of the PT equation was unclear (e.g., MONTEITH and UNSWORTH, 1990). Therefore, examining $Rn/S^{\downarrow}$ values was not strongly required in the past. The theoretical background of the PT equation is now fairly clear as a result of many theoretical and experimental studies (e.g., BALDOCCHI *et al.*, 1997, 2000; RAUPACH, 1998). Consequently, the PT equation has been used in recent years to estimate evapotranspiration rates of forests (e.g., KUMAGAI *et al.*, 2004a,b, 2005; KOMATSU *et al.*, 2005), and examining $Rn/S^{\downarrow}$ values is now strongly required.

It is expected that constant $Rn/S^{\downarrow}$ values are applicable to *Rn* estimates in all seasons. $Rn/S^{\downarrow}$ can be written as $Rn/S^{\downarrow} = (1 - S^{\uparrow}/S^{\downarrow}) + L^{*}/S^{\downarrow}$, where $S^{\uparrow}$ is the upward solar radiation and L^{*} is the net long-wave radiation (e.g., MONTEITH and UNSWORTH, 1990). Albedo $S^{\uparrow}/S^{\downarrow}$ usually shows small seasonal changes (e.g., HATTORI, 1984). $L^{*}/S^{\downarrow}$ is usually much smaller than $(1 - S^{\uparrow}/S^{\downarrow})$ during daytime (e.g., HATTORI, 1986). Thus, $Rn/S^{\downarrow}$ values will show small seasonal changes.

To clarify whether constant $Rn/S^{\downarrow}$ values are usable to *Rn* estimates in all seasons, it is necessary to examine seasonal changes in $Rn/S^{\downarrow}$ values for various types of forests. As part of such examinations, we examined seasonal changes of $Rn/S^{\downarrow}$ values for a coniferous evergreen plantation forest of *Cryptomeria japonica* in Japan. The *C. japonica* forest type is quite common in Japan (FUJIMORI, 2000), which makes examining $Rn/S^{\downarrow}$ values of this type of forest especially important for consideration of forest water and/or carbon cycles in Japan.

II. Materials and methods

We used 1-year radiation and air temperature data obtained in 1998 at the Shinta experimental site.

The Shinta experimental site is located in Chiba Prefecture, Japan (35°12'N, 140°06'E, elevation 236 m). An 11-m observation tower was installed at this site, and meteorological data have been measured since 1996. The annual rainfall in 1998 was 2,510 mm and the mean annual

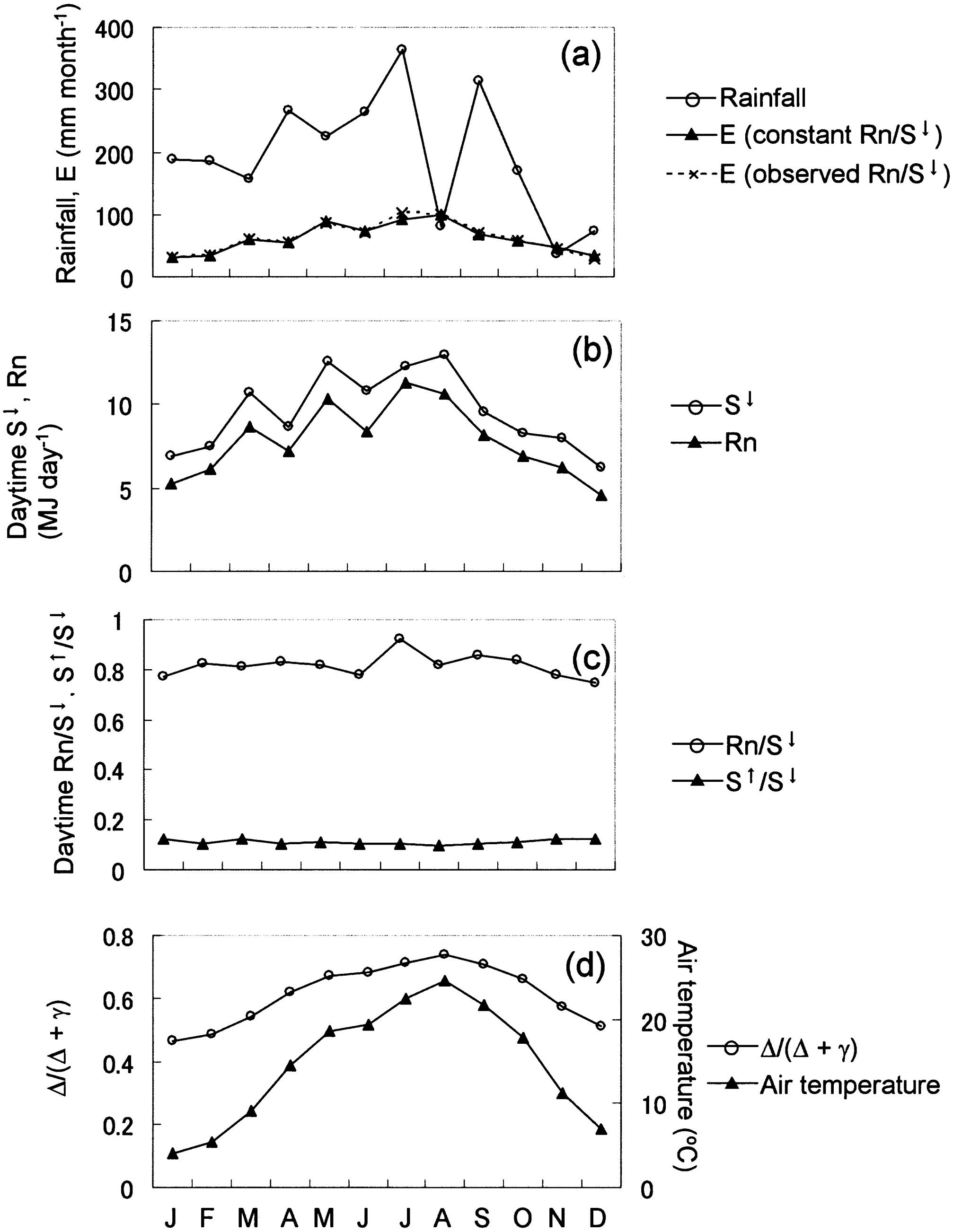

Fig. 1. Seasonal changes in (a) rainfall and evapotranspiration rates E estimated by Eq(2) based on constant $Rn/S^{\downarrow}$ (= 0.82) and observed $Rn/S^{\downarrow}$, respectively; (b) daytime $S^{\downarrow}$ and Rn; (c) daytime $Rn/S^{\downarrow}$ and $S^{\uparrow}/S^{\downarrow}$; (d) $\Delta/(\Delta + \gamma)$ and air temperature. $\alpha = 1.0$ was assumed for E estimates. The term "daytime" indicates the period with positive $S^{\downarrow}$.

temperature in 1998 was 15.0 °C. Seasonal changes in rainfall and air temperature are shown in Figure 1a and 1b, respectively. *Cryptomeria japonica* trees were planted at this site in 1980. In 1998, the mean tree height was 7.5 m, and the stand density was 1,300 stems per hectare. The projected leaf area index (LAI), estimated using a plant canopy analyzer (Li-Cor, LI-2000), was 3.7 ± 0.3. This value of projected leaf area index can be converted into 8.9 in total surface area index by assuming the converting factor of 2.4 which is intermediate for conifers (LANDSBERG and GOWER, 1997).

Radiation and air temperature measurements were performed above the forest canopy. Downward and upward solar radiation were measured using pyranometers (Eko, MS-42) at 10-minute intervals, and net radiation was measured using a net radiometer (Eko, MF-11) at 10-minute intervals. Downward and upward long-wave radiation were measured using pyrgeometers (Eko, MS201F) at 20-minute intervals starting in September 1998. Net radiation calculated based on solar and long-wave radiation measurements differed by on average 2% with that based on net radiometer measurements for this site (YOSHIFUJI and KANG, 2002). Air temperature was measured using a thermometer (VAISALA, VHE) at 10-minute intervals. A more complete description of the site and all measurements was provided by KOMATSU *et al.* (2006a).

Based on the radiation data, we calculated the average monthly daytime $Rn/S^{\downarrow}$ values for 1998. Daytime Rn and $S^{\downarrow}$ data were averaged to obtain average monthly daytime Rn and $S^{\downarrow}$. The average monthly daytime $Rn/S^{\downarrow}$ was calculated from the average monthly daytime Rn and $S^{\downarrow}$. Similar to $Rn/S^{\downarrow}$, we also calculated the average monthly daytime $S^{\uparrow}/S^{\downarrow}$. Due to missing data, 91% of the data potentially available for the year were included in the calculations.

III. Results and discussion

Figure 1b shows seasonal changes in daytime Rn and $S^{\downarrow}$. Figure 1c shows seasonal changes in $Rn/S^{\downarrow}$ and $S^{\uparrow}/S^{\downarrow}$. The $Rn/S^{\downarrow}$ showed slight seasonal changes (Figure 1c), and the average (± SD) of $Rn/S^{\downarrow}$ was 0.82 (± 0.04). The $Rn/S^{\downarrow}$ value was relatively higher in July because of cloudy weather in this month which was suggested by rainfall data (Figure 1a) and because of $L^{*} \sim 0$ for cloudy days (e.g., MONTEITH and UNSWORTH, 1990). The average value of 0.82 was nearly identical to the $Rn/S^{\downarrow}$ value of 0.8 reported by JARVIS *et al.* (1976) based on literature survey.

The albedo $S^{\uparrow}/S^{\downarrow}$ also showed slight seasonal changes, which supported the slight seasonal changes in $Rn/S^{\downarrow}$. The average (± SD) of $S^{\uparrow}/S^{\downarrow}$ was 0.11 (± 0.01). This value was nearly identical to the $S^{\uparrow}/S^{\downarrow}$ value reported in earlier papers (e.g., JARVIS *et al.*, 1976; HATTORI, 1984). JARVIS *et al.* (1976) surveyed earlier publications and found that the value of $S^{\uparrow}/S^{\downarrow}$ ranged from 0.05 to 0.2 for coniferous evergreen forests, and the value of $S^{\uparrow}/S^{\downarrow}$ was typically 0.1.

As described below, the slight seasonal changes in $Rn/S^{\downarrow}$ suggests that assuming a constant $Rn/S^{\downarrow}$ for all seasons is valid for this site when calculating seasonal changes in E based on the PT equation.

When we ignore G in Eq(1) by assuming $G << Rn$, Eq(1) reduces to

$$E = \alpha \frac{\Delta}{\Delta + \gamma} \frac{Rn}{\lambda} = \alpha \frac{\Delta}{\Delta + \gamma} \frac{Rn}{S^{\downarrow}} \frac{S^{\downarrow}}{\lambda}. \quad (2)$$

This equation indicates that the seasonal change in E is determined by the seasonal change in α, $\Delta/(\Delta + \gamma)$, and $S^{\downarrow}$, as well as $Rn/S^{\downarrow}$. As Δ varies with air temperature, $\Delta/(\Delta + \gamma)$ depends on air temperature (e.g., MONTEITH and UNSWORTH, 1990).

For our site, $\Delta/(\Delta + \gamma)$ and $S^{\downarrow}$ showed large seasonal changes, in contrast to $Rn/S^{\downarrow}$. Both $\Delta/(\Delta + \gamma)$ and $S^{\downarrow}$ were higher in summer and lower in winter. $\Delta/(\Delta + \gamma)$ was highest in August and lowest in January, since air temperature was highest in August and lowest in January (Figure 1d). The $\Delta/(\Delta + \gamma)$ values were 0.74 and 0.46 in August and in January, respectively. The $S^{\downarrow}$ was highest in August and lowest in December (Figure 1b). The $S^{\downarrow}$ values were 12.9 (MJ m^{-2} d^{-1}) and 6.21 (MJ m^{-2} d^{-1}) in August and December, respectively.

In addition, α would show large seasonal changes according to earlier papers. α values were unavailable for our site. However, ARAIN *et al.* (2003) and RESTREPO and ARAIN (2005) have reported large seasonal changes in α on coniferous evergreen forests, where α was greater during the growing season than during the winter. Furthermore, work by KOMATSU *et al.* (2006b) indicated large seasonal changes in canopy conductance at our site. KOMATSU *et al.* (2006b) found that canopy conductance was greater during the growing season than during the winter. This implies a large seasonal change in α as well, because α is positively correlated with surface conductance (BALDOCCHI *et al.*, 1997, 2000; RAUPACH, 1998), and because canopy conductance approximates surface conductance when projected LAI ≥ ca.3 (KELLIHER *et al.*, 1995).

From the above, the seasonal change in E calculated by the PT equation is determined by the seasonal change in $\Delta/(\Delta + \gamma)$ and $S^{\downarrow}$ rather than the seasonal change in $Rn/S^{\downarrow}$for our site. Thus we conclude that assuming constant $Rn/S^{\downarrow}$ for all seasons is valid for our site when calculating seasonal changes in E based on the PT equation. Figure 1a shows E estimated by Eq(2) based on constant $Rn/S^{\downarrow}$ (= 0.82) throughout the year and based on observed $Rn/S^{\downarrow}$, respectively. In these estimates, α = 1.0 was assumed for simplicity. E based on constant $Rn/S^{\downarrow}$ showed similar seasonal changes with E based on observed $Rn/S^{\downarrow}$.

Assuminig constant α is now considered as problematical for most forest canopies (JARVIS and MCNAUGHTON, 1986; KOMATSU, 2005). Thus, recent studies use the PT equation for estimating evapotranspiration rates from forests with parameterization of α values (e.g., KUMAGAI *et al.*, 2004a,b; KOMATSU *et al.*, 2005). However, the constant α assumption given in this study does not violate our conclusions. If α varies seasonally, seasonal changes in E depends on sesaonal changes in α as well as seasonal changes in $\Delta/(\Delta + \gamma)$ and $S^{\downarrow}$. Thus, considering seasonal changes in $Rn/S^{\downarrow}$ is less important when α varies seasonally than when α is seasonally constant.

It is still unclear whether assuming constant $Rn/S^{\downarrow}$ is generally valid for various types of forests. To our knowledge, this paper is the first to examine seasonal changes in daytime $Rn/S^{\downarrow}$ values for a forest. Therefore, we recommend further studies that examine seasonal changes in $Rn/S^{\downarrow}$ values of other forest sites to assess the generality of our conclusions. In particular, we highly recommend studies that examine seasonal changes in $Rn/S^{\downarrow}$ values of deciduous forests.

These forests generally show more significant seasonal changes in albedo than evergreen forests due to their drastic change in LAI (e.g., SCHMID *et al.*, 2000; KNOHL *et al.*, 2003). This implies $Rn/S^{\downarrow}$ values may have larger seasonal changes in these forests than those presented in this study. Therefore, assuming constant $Rn/S^{\downarrow}$ values may not be valid for these forests.

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Summary

The Priestley-Taylor (PT) equation requires net radiation *Rn* as input. *Rn* is often unavailable from many meteorological datasets. *Rn* may be estimated from downward solar radiation $S^{\downarrow}$ assuming $Rn/S^{\downarrow}$ values. We examined seasonal changes of $Rn/S^{\downarrow}$ values using 1-year radiation data observed above a coniferous evergreen plantation forest of *Cryptomeria japonica*. $Rn/S^{\downarrow}$ showed slight seasonal changes; however, other terms in the PT equation showed large seasonal changes. Thus, we conclude that assuming constant $Rn/S^{\downarrow}$ for all seasons is valid for this site.

Key words: *Cryptomeria japonica* plantation, Evapotranspiration, Net radiation, Priestley-Taylor equation, Solar radiation

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スギ人工林における純放射量と日射量の比の季節変化

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要　　　旨

Priestley-Taylor式（PT式）は純放射量*Rn*の入力を必要とする。しかし，*Rn*は気象データセットに含まれていないことが多い。*Rn*がデータセットから得られない場合，*Rn*と下向き日射量$S\downarrow$の比を仮定することで，*Rn*を$S\downarrow$から推定するという方法が考えられる。本研究では，スギ人工林上で計測された*Rn*と$S\downarrow$のデータから，$Rn/S\downarrow$の季節変化を調べた。$Rn/S\downarrow$はわずかに季節変化を示したが，その季節変化はPT式のほかの項の季節変化に比べて小さかった。したがって，$Rn/S\downarrow$を季節によらず一定と仮定することは，本研究の対象とした試験地において妥当であると結論された。

キーワード： スギ人工林・蒸発散・純放射・Priestley-Taylor式・日射