B-1.6 Modeling of energy exchange between a forest ecosystem and the atmosphere

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Total Budget for FY1997-FY1999 12,688,000 Yen (FY1998; 4,222,000 Yen)

Abstract

This sub-theme is aiming at a development of a relevant parameterization for the exchange process between a forest ecosystem and the atmosphere.

To obtain basic data for the parameterization, a long-term tower observation of the energy exchange between a forest and the atmosphere has been continuously conducted over a deciduous broad-leaf forest in Kawagoe, Japan. The observation also covers microclimate within the forest, soil moisture and temperature, leaf area, etc. , as controlling environments. To keep quality of data, the maintenance of instruments was made carefully, and many different techniques were adopted in parallel for each measurement. The observed results show that the albedo and each component of the energy budget of the forest exhibit clear seasonal variation, correlating well with the seasonal change in the leaf area index. A proper consideration of the phenological cycle is hence necessary for a parameterization of the energy exchange over a deciduous forest.

Applying a simple canopy model to the obtained data, the evaporation efficiency of the forest (the most important parameter to model the energy budget) was estimated. The results show that the value of evaporation efficiency has seasonal and diurnal variations. The seasonal variation is induced by the phenological change in the tree activity, and the diurnal variation comes from the stomatal regulation which responds to the meteorological condition. As the first step of the parameterization, the dependency of evaporation efficiency to the meteorological condition was modeled simply with the solar radiation and the evaporative demand (expressed in terms of the potential evaporation rate) of the atmosphere. The diurnal variation of energy budget of the forest was then successfully simulated using this parameterization.

Key Words Land-surface process, Forest, Energy budget, Long-term observation, Parameterization

1. Introduction

Through the exchange process with the atmosphere, forests exert an influence on the thermal distribution in the lower atmosphere, which induces the atmospheric circulation and thus modify the climate. Forests adjust their behavior to their environmental conditions, thereby controlling the exchange process with the atmosphere. The influence of forests on the atmosphere therefore varies depending on their biological responses. These biological processes have not been incorporated adequately in the atmospheric circulation or climate models. The biological process, however, is one of the most important processes for a long-term forecast of the global climate.

On the other hand, a worldwide experimental project FLUXNET is now going on, in which the surface fluxes of energy, water vapor, and carbon dioxide are routinely observed and compiled for a variety of land surface ecosystem. The data compiled in the project will be very useful to quantify the seasonal variations of the fluxes due to annual changes in meteorological and biological conditions, to understand the biological and meteorological processes that control the fluxes, and to test land-surface schemes (Baldocchi et al., 1996). The FLUXNET has been started mainly on the North American and European continents, and participation from Asian countries have been encouraged. Recently, a group of Japanese researchers launched the AsiaFlux that covers the flux observations in Asian countries and takes part in the worldwide FLUXNET (Fukushima, 2000).

2. Research objective

This sub-theme is aiming at a development of a relevant parameterization for the exchange process between a forest ecosystem and the atmosphere. On this purpose, actual variations in the exchange process must be quantified by an experimental study, and through which problems in current land-surface schemes must be clarified. Furthermore, the experimental study should be continued as long as possible because there is much uncertainty in the response of forests to a long-term variation of environmental conditions. Although the final goal of the research is to obtain a perfect parameterization that can handle both short- and long-term variations in the exchange process, the present 3-year project is focused on a parameterization of the short-term responses to changes in environmental conditions.

3. Research method

3.1 Field experiment

Long-term measurements are conducted at an experimental forest site at Kawagoe, Japan. The measurements cover the fluxes of energy, water vapor and carbon dioxide, microclimate within and above the forest canopy, soil moisture and temperature, forest architecture, and others. A 25-m tower is utilized for the measurements. To enhance the quality of data, all instruments are carefully maintained during the measurement and various different techniques are concurrently adopted for some quantities (e.g., the eddy correlation method and the Bowen ratio / energy balance method for the energy flux). Among others, a new technique is developed and adopted for the measurement of water vapor flux. Using the obtained data, the relationship between the exchange process and biological or environmental conditions is investigated.

3.2 Parameterization

The evaporation efficiency is a key parameter in developing a simple land-surface scheme. However, it is not well known for forests how much the quantity is and how the quantity varies in response to changes in biological and environmental conditions. In the present study, therefore, the evaporation efficiency of the forest is estimated from the experimental data, and its diurnal and seasonal variations are quantified and parameterized. The estimation is using the following 3-equation model (Watanabe, 1994).

1) Energy budget of the underlying ground surface

$$m_s S_n + m_L L^{\downarrow} + (1-m_L)\sigma T_c^4 = \sigma T_g^4 + c_p \rho C_{Hg} u(T_g - T) + l\rho\beta_g C_{Hg} u\left[q^*(T_g) - q\right] + G$$

2) Energy budget of the canopy

$$(1-m_S)S_n + (1-m_L)\left(L^{\downarrow} + \sigma T_g^4\right) = 2(1-m_L)\sigma T_c^4 + c_p \rho C_{Hc} u(T_c - T) + l\rho\beta_c C_{Hc} u\left[q^*(T_c) - q\right]$$

3) Sensible heat flux above the canopy

$$H = c_p \rho C_{Hg} u(T_g - T) + c_p \rho C_{Hc} u(T_c - T)$$

In these equations, the shortwave and longwave transmissivities of the canopy (m_S and m_L), and the bulk transfer coefficients for the sensible heat (C_{Hg} and C_{Hc}) are prescribed, referring to the forest height and the leaf area index. The evaporation efficiency of the ground surface is assumed as $\beta_g = 1$, since an extremely dry condition was not experienced and the

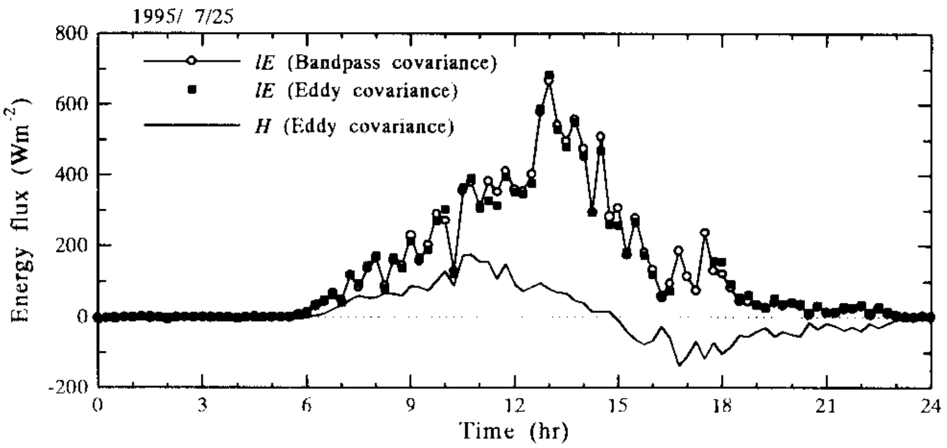

Figure 1. Comparison between the new method (open circle) and the ordinary eddy covariance method (filled square) for a diurnal cycle of water vapor flux.

result is not sensitive to this parameter. Using measured values for the meteorological condition (S_n, $L^{\downarrow}$, u, T, q), the soil heat flux G and the sensible heat flux H, these three equations can be solved for three unknown values of the soil surface temperature T_g, the canopy temperature T_c and the evaporation efficiency of the canopy β_c.

4. Results and discussion

4.1 New technique for measuring the water vapor flux

In order to make a direct measurement of the water vapor flux for long period of time, the advanced bandpass eddy covariance method was developed (Watanabe et al., 2000). In the method, a general-purpose humidity sensor is utilized for the eddy covariance technique, introducing a correction using the frequency response function of the sensor. The new method was verified against the ordinary eddy covariance method using a fast-response open-path gas analyzer as shown in Fig.1.

4.2 Seasonal variations in observed results

Figure 2 shows the seasonal variation in the leaf area index (LAI). The LAI was estimated by the combined measurements of the litter-fall and the light penetration rate through the canopy. The leaf emergence is observed in the middle of April, and LAI reached its maximum (LAI=6) in June. The LAI then kept higher values showing a slight decrease until the end of October, followed by a steep decrease. The leaf-fall was completed by the end of the year.

The value of albedo varied around 0.1 during the year as shown in Fig. 3. The albedo jumped from 0.07 to 0.14 at the time of the leaf emergence, followed by a gradual decrease as leaves matured. A slight increase observed in October and November may be due to the leaf senescence. These results indicate that the timing of leaf emergence and seasonal variation in the optical properties of leaves are both important for modeling the seasonal trend of the albedo.

Figure 4 shows the seasonal variation in the energy budget, expressed in terms of 10-day average of (energy balance / Bowen ratio) fluxes integrated during the daytime. The figure clearly documents that the sensible heat dominates the latent heat in the leafless season when the evaporative demand is low and the underlying soil surface is the only source of water vapor, but this is totally reversed in the growing season when both the leaf activity and

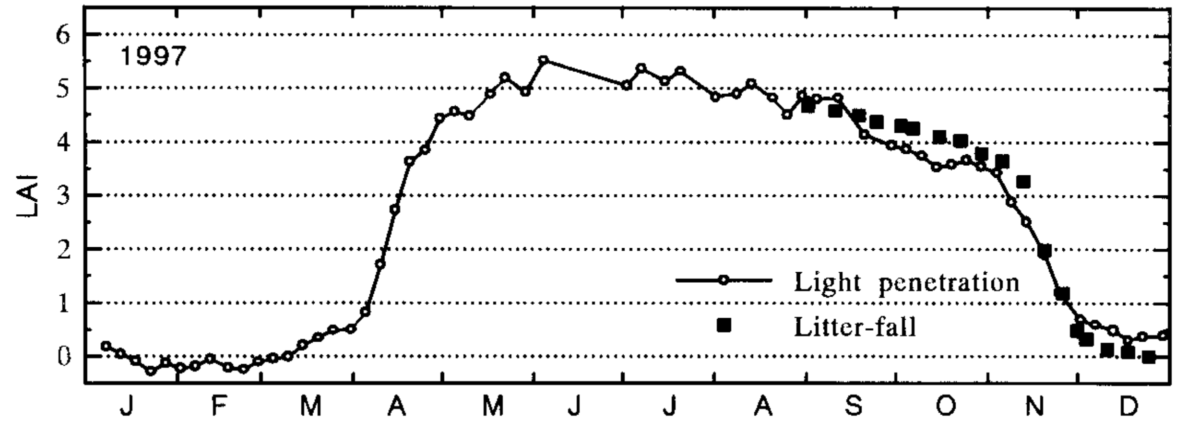

Figure 2. Seasonal variation of the leaf area index for 1997, estimated by the light measurements (open circles) and the litter-fall (filled squares).

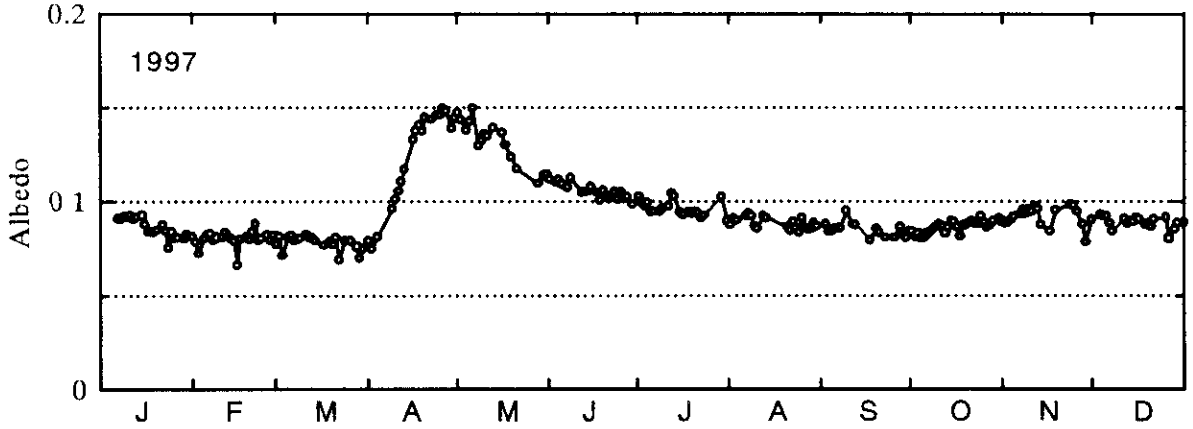

Figure 3. Seasonal variation of the albedo for 1997, averaged over midday hours (1000-1400).

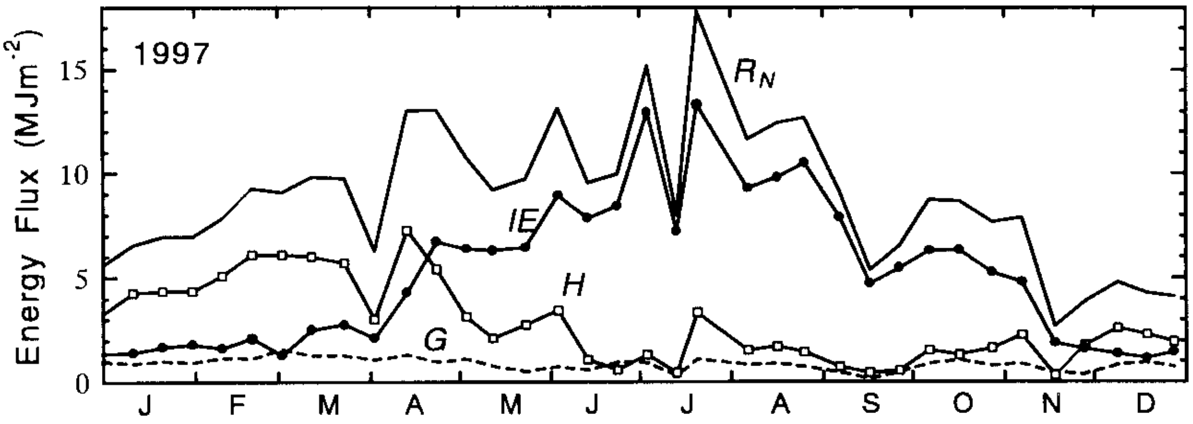

Figure 4. Seasonal variation in the daytime energy budget for 1997, averaged over 10 days. (R_N : net radiation, G : heat storage rate, H : sensible heat, lE : latent heat)

the evaporative demand are very high. The correlation between the energy partitioning and the LAI is clear.

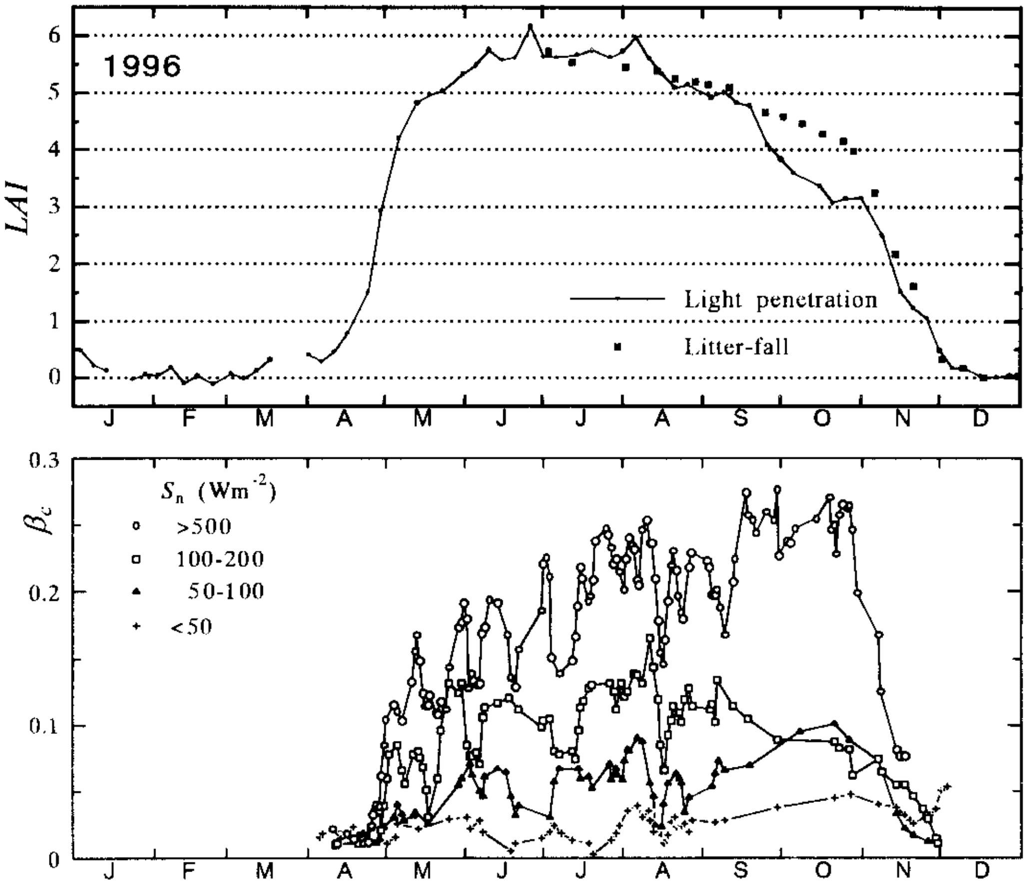

Figure 5. Seasonal variations in the leaf area index (top) and the evaporation efficiency (bottom) for 1996. Values of the evaporation efficiency shown are 3-day averages.

4.3 Parameterization of evaporation efficiency

The seasonal variation of the evaporation efficiency for 1996 is presented in Fig. 5 along with the seasonal variation of LAI. The value of the evaporation efficiency rapidly increases at the same time with the leaf emergence and continued to increase until November. The value was then decreased during the leaf-fall. This is the first result showing both the value of the evaporation efficiency and its seasonal variation. The figure also shows that the values increase as the shortwave radiation increases. Shorter time-scale variations observed in the figure are correlated well with the potential evaporation rate, which represents the evaporative demand of the atmosphere. This implies trees in the forest close their stomata to prevent extensive water loss in dry conditions.

These stmatal responses are normally modeled using many functions that describe dependencies on the shortwave radiation, air temperature, saturation deficit of the air, the leaf water potential, separately (Jarvis, 1976). However, in the present study, the evaporation efficiency is simply parameterized by the shortwave radiation and the potential evaporation, on the ground that the stomatal aperture is mainly controlled by the shortwave radiation absorbed by the leaf and the water status in the leaf surface unless the tree is not affected by severe water stress. This is expressed as:

$$\beta_c = \beta_{\max} F_S(S_n) F_E(E_p),$$

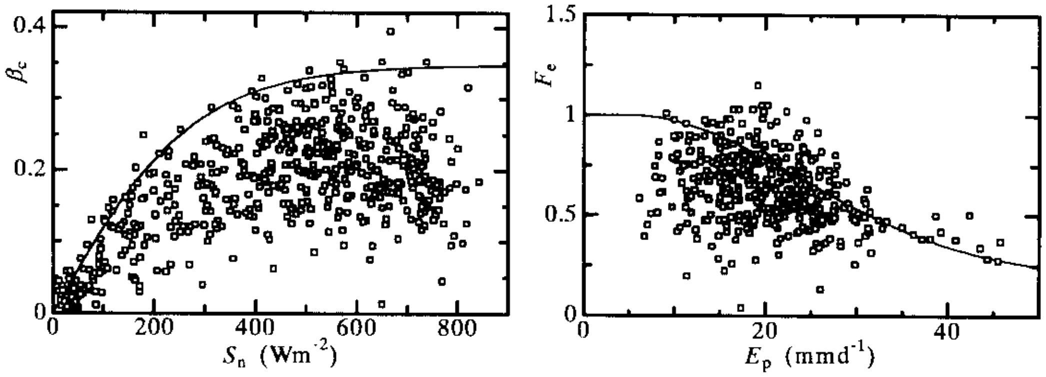

Figure 6. Dependencies of the evaporation efficiency on the shortwave radiation (left) and the potential evaporation rate (right). Plots are estimated values from measurements and curves denote the present parameterization.

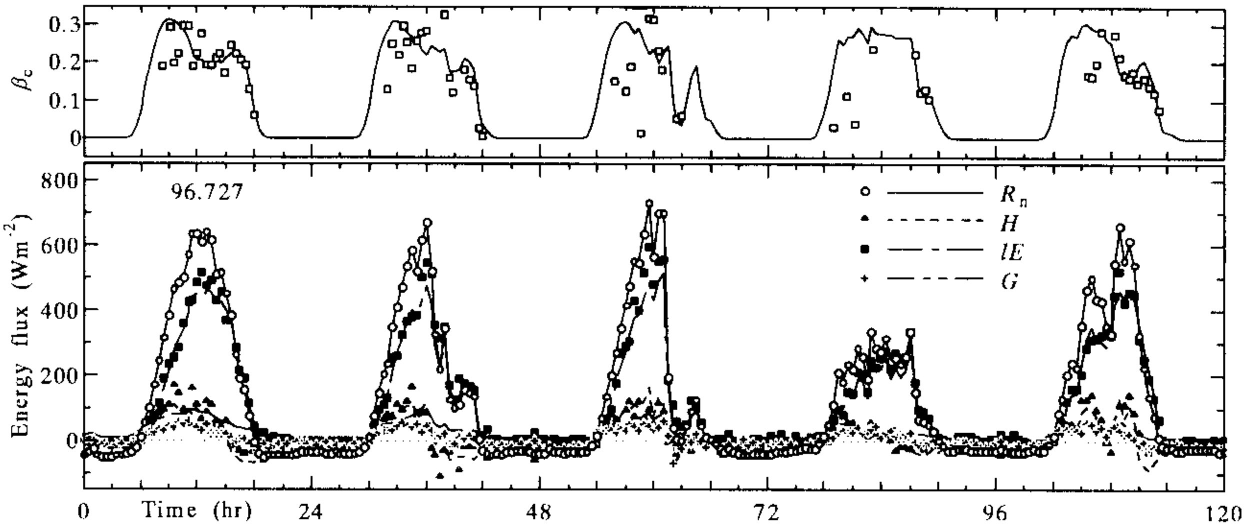

Figure 7. Comparison between modeled results (curves) and measurements (plots) in the evaporation efficiency (top) and the energy budget (bottom).

where $\beta_{\max}$ is the maximum evaporation efficiency, while F_S and F_E are mathematical functions describing the dependency on the shortwave radiation and the potential evaporation, respectively. Functional forms of F_S and F_E are determined in the following.

The left panel of Fig. 6 shows the evaporation efficiency evaluated at every 30 minutes in the summer season, plotted versus the net shortwave radiation above the canopy. It is well known that the stomatal aperture increases as the shortwave radiation increases and saturates at a certain level. The line in the same panel is the determined functional form for $\beta_{\max}F_S$, which represents the potential evaporation efficiency for non-regulated cases; otherwise it is decreased by some limiting effects. All values are then divided by $\beta_{\max}F_S$ and plotted versus the potential evaporation in the right panel of Fig. 6. Although plots are largely scattered, it is clear that the evaporation efficiency is limited when the potential evaporation is very large. The function F_E is thus determined as the solid line shown in the panel. Using this parameterization for the evaporation efficiency, variations in the energy budget are

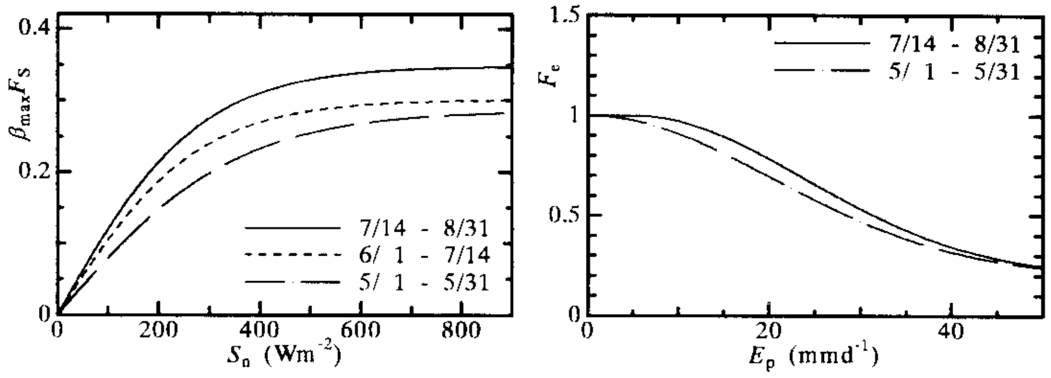

Figure 8. Seasonal difference in the evaluated dependencies of the evaporation efficiency on the shortwave radiation (left) and the potential evaporation rate (right).

summarized in Fig. 7. The model correctly simulated both the evaporation efficiency and the energy budget of the forest.

In the same manner as shown above, the functions of F_S and F_E are determined for different seasons as shown in Fig. 8. The same mathematical form can be used for all seasons but different parameters are detected for each season. The figure shows that the function $\beta_{max}F_S$ increases from spring to summer but difference in F_E is not large for all seasons. Using these functions, the energy budget of the forest can be simulated for all seasons.

A next step of this research would be to investigate mechanisms involved in seasonal or inter-annual variations in the albedo, the energy budget, and the evaporation efficiency in order to develop relevant parameterizations for longer time-scale variations.

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