

# Interannual variation of evapotranspiration in an eastern Siberian larch forest

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## Abstract

In a deciduous larch forest in eastern Siberia, the mean and standard deviation of the total evapotranspiration ( $E$ ) during May to September (day of year (DOY) = 121–274) for 2003–2006 were 181.5 and 26.4 mm, respectively. The interannual variation (IAV) in the total  $E$  was caused by the IAV in  $E$  for the canopy-foliated period (DOY = 164–253), not by the IAV in the dates of leaf expansion and leaf fall. For the years with higher total  $E$ ,  $E$  in the canopy-foliated period was consistently higher, which corresponded to the higher soil water content in these years. Copyright © 2012 John Wiley & Sons, Ltd.

**Key words** boreal deciduous forest; evapotranspiration; interannual variation; leaf expansion; leaf fall; eastern Siberia

## Introduction

Evapotranspiration ( $E$ ) is a major component of the terrestrial water cycle and has important influences on river flow regimes, ground water recharges, and local and regional climate (Brown *et al.*, 2005; Bonan, 2008; Komatsu *et al.*, 2008, 2011). Many researchers have examined  $E$  in various types of terrestrial ecosystems (Granier *et al.*, 2000; Kumagai *et al.*, 2004, 2008; Komatsu, 2005). Of these, large areas are occupied by the boreal forest (FAO, 2005), which plays an important role in the global water cycle (Bonan *et al.*, 1995; Jarvis *et al.*, 2001; Bonan, 2008). For example, Bonan *et al.* (1995) highlighted the importance of land surface parameterization for boreal regions using a global circulation model. This demonstrates the importance of studies examining energy exchanges (including  $E$ ) for boreal regions. However, relatively few such studies have been conducted in the boreal forests (Baldocchi *et al.*, 1997; McCaughey *et al.*, 1997; Cienciala *et al.*, 1998; Mkhabela *et al.*, 2009).

Among the studies examining  $E$  in boreal forests, most were performed in Europe and North America (Sellers *et al.*, 1995, 1997; Baldocchi *et al.*, 1997; Cienciala *et al.*, 1998; Halldin *et al.*, 1999; Mkhabela *et al.*, 2009). Few studies (Kelliher *et al.*, 1997, 1998; Ohta *et al.*, 2001, 2008; Matsumoto *et al.*, 2008) have been conducted in the large boreal forests of Siberia, particularly in eastern Siberia. The eastern Siberian boreal forests differ from their counterparts in Europe and North America in terms of specific meteorological conditions (relatively low temperature and precipitation, Baldocchi *et al.*, 2000), presence of continuous permafrost (Ohta *et al.*, 2008), and tree species (deciduous larch, Kelliher *et al.*, 1997). This suggests that results obtained in other parts of boreal forests might not be applicable to forests in eastern Siberia; thus, it is important to examine  $E$  in this region.

Kelliher *et al.* (1997, 1998) conducted the first studies on  $E$  within the forests of eastern Siberia. They measured  $E$  during several days in summer in a larch forest and examined relationships between  $E$  and environmental factors, such as radiation, vapor pressure deficit (VPD), and soil water content (SWC). More recently, Ohta *et al.* (2008) measured  $E$  and various environmental factors in a larch forest during May–September over seven years to identify the factors causing interannual variation (IAV) in  $E$ . They assumed that  $E$  in winter was very

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small and, therefore, negligible because of very low temperature (Ohta *et al.*, 2008), which is supported by the results from studies in other boreal sites (Grelle *et al.*, 1999; Arain *et al.*, 2003; Pejam *et al.*, 2006). Ohta *et al.* (2008) found a relationship between SWC and  $E$ , which suggested that SWC was the main factor determining IAV of  $E$  at their site.

Ohta *et al.*'s (2008) research was valuable in that it was the first study examining IAV in  $E$  for a boreal deciduous forest in eastern Siberia. However, to analyse the IAV in  $E$ , they used the total  $E$  measured during May–September. Thus, processes producing the variations of  $E$  have not been sufficiently examined in two respects. First, Ohta *et al.* (2008) did not consider the effects of IAV in the dates of leaf expansion and leaf fall on the IAV in total  $E$ . The IAV in the dates of leaf expansion have been found to be greater in the boreal forests of eastern Siberia (Ishida, 2009) than those reported for temperate forests (Wilson and Baldocchi, 2000; Granier *et al.*, 2002), although the IAV in the dates of leaf fall were similar. Thus, the IAV in the dates of leaf expansion might play a role in determining IAV of the total  $E$  during May–September. Second, Ohta *et al.* (2008) did not clarify whether higher or lower total  $E$  in particular years was caused by consistent higher or lower  $E$  throughout the measurement period or whether it was caused by relatively extreme values collected during specific time points within this period. In this study, we aimed to investigate the importance of these two issues, which have so far been overlooked for the boreal forests of eastern Siberia, to help the development of a mechanistic, process-based understanding of factors causing IAV in  $E$ .

## Materials and Method

### Data collection

Data were collected in a larch forest in eastern Siberia (62°15'18"N, 129°37'08"E, altitude 220 m) in a continuous permafrost region. The soil in this site was classified as sandy loam. The mean annual temperature at the site during 1998–2006 was  $-9.5^{\circ}\text{C}$  (Ohta *et al.*, 2008), with a minimum temperature of  $-55^{\circ}\text{C}$  occurring in the mid-winter of 1998. The mean annual precipitation during 1998–2006 was 259.2 mm but also was highly seasonal, ranging from around 69.0 mm during October–April to around 190.3 mm during May–September (Ohta *et al.*, 2008). Snow cover generally lasted from early October to the following late April.

The larch forest was characterized by two stories of vegetation. The overstory was composed of 160-year-old deciduous larch (*Larix cajanderi*), with a stand density of 808 trees  $\text{ha}^{-1}$  and a mean basal area of  $27.6\text{ m}^2\text{ ha}^{-1}$  (Matsumoto *et al.*, 2008). The average tree height of the overstory was approximately 21 m, and the leaf area index (LAI) of the canopy, measured using a LAI-2000 plant canopy analyser (LI-COR, Lincoln, NE, USA), was 1.6 in 2005. The understory was dense and composed of evergreen

cowberry (*Vaccinium vitis-idaea*). The height of the understory was 0.05 m, and its LAI was 2.1 based on destructive measurements in 2005 (Miyahara, 2005). Although there were no records of disturbance history, there was no evidence of any large disturbances considering the tree age.

A 32-m observation tower at this site was used to measure  $E$  and various environmental factors over a four-year period (2003–2006). In detail,  $E$  was measured using a three-dimensional sonic anemometer (WindMaster Pro, Gill, Hampshire, UK) with an open-path  $\text{CO}_2/\text{H}_2\text{O}$  analyser (LI-7500, LI-COR, Lincoln, NE, USA) positioned at the top of the observation tower. The fetch of the site was 2–4 km from all directions of the tower. According to the footprint analysis based on Horst and Weil (1992, 1994), the distance of the maximum upwind footprint from the tower was 18 m (12:30 h, 2 August 2006) and 33 m (7:30 h, 13 August 2006) for two typical unstable and near-neutral cases (Obukhov length ( $L$ ) were  $-100$  and  $2287$  m, respectively). In addition, the distance where the cumulative flux occupied 90% of the total flux also was calculated at 30-minute interval for the whole measurement period. The average distance were 384 m under unstable conditions ( $(z-d)/L < -0.1$ ) and 1090 m under near-neutral conditions ( $-0.1 < (z-d)/L < 0.1$ ) from the tower, respectively. Here,  $z$  is the measurement height (32.0 m), and  $d$  is the zero-plain displacement (7.35 m from Nakai *et al.*, 2008). For this analysis, the momentum roughness length was determined as 3.16 m using measured wind-speed profile data (see Nakai *et al.*, 2008), and other inputs (i.e. friction velocity, wind speed at measurement height and  $L$ ) were from measured data at 30-minute interval. Wind speeds and a gas concentration time series were sampled at 10 Hz (CR5000 data logger, Campbell Scientific). All variances and covariances required for the eddy covariance flux estimates were computed with a 30-min averaging interval. The wind field coordinates were rotated so that the mean lateral and vertical wind speeds were zero over 30-min periods. The  $E$  data were corrected using Webb correction (Webb *et al.*, 1980). The data collected during precipitation also were omitted, and the omitted data accounted for 23% of the whole  $E$  data in number. We then assigned the missing values using the multiple imputation method (MIM) (Hui *et al.*, 2004) with the "NORM" software (<http://www.stat.psu.edu/~jls/misoftwa.html>), as carried out by Ohta *et al.* (2008). The MIM method is a stochastic model that computes missing  $E$  data with the input of environmental variables. In our case, we used solar radiation, wind speed, relative humidity, and SWC as inputs. A detailed description of the data quality can be found in Ohta *et al.* (2008).

Downward and upward solar radiation above the canopy and downward solar radiation under the canopy were measured using pyranometers (MS402F, EKO, Tokyo, Japan and CM-6 F, Kipp & Zonen, Delft, the Netherlands) situated 32.0, 27.9 and 2.0 m above the ground, respectively. Downward and upward photosynthetic photon flux density

(PPFD) above the canopy and downward PPFD under the canopy were measured using quantum sensors (LI-190, LI-COR, Lincoln, NE, USA) situated at 32.0, 27.9, and 4.5 m above the ground, respectively. Downward and upward longwave radiation were measured using pyrgeometers (MS202F and MS201F, EKO, Tokyo, Japan) situated 32.0 and 27.9 m above the ground, respectively. Temperature and relative humidity were measured using a thermohygrograph (HMP45D, Vaisala, Helsinki, Finland) at a height of 31.4 m. SWC was measured using time-domain reflectometry (TRIME-FM2/P2, IMKO, Japan) at depths of 10, 20, 40, 60 and 80 cm at a site 10 m south of the tower. As we did not have SWC data at other points in the site, we could not examine spatial variance of SWC at the site. Because of the flat topography (Ohta *et al.*, 2001), we assumed that the measured SWC data represented the SWC of the site (see also Matsumoto *et al.*, 2008; Ohta *et al.*, 2008). In the analysis, we used SWC data for 0–50 cm depth and calculated the weighted average, assuming that the SWC at 10, 20, and 40 cm depths represented SWC at 0–15, 15–30, and 30–50 cm, respectively (Matsumoto *et al.*, 2008; Ohta *et al.*, 2008). Soil heat storage was measured at a depth of 5 cm in 2003 and 2004 using a heat flux plate (PHF-01, REBS, USA) and at a depth of 1 cm after 2004 using another heat flux plate (MF-81, Eiko, Japan) at the same site with the SWC. Precipitation was measured at an open site 1 km south of the tower using a tipping-bucket rain gauge with 0.13 mm accuracy.

The dates of leaf expansion and leaf fall were analysed using the reflection coefficient (ratio of above-canopy upward solar radiation or PPFD to above-canopy downward solar radiation or PPFD) and the transmission coefficient (ratio of below-canopy downward solar radiation or PPFD to above-canopy downward solar radiation or PPFD) (Ishida, 2009). The results showed that compared with the reflection coefficients, the transmission coefficients of solar radiation and PPFD were better indicators of the leaf phenological changes. This was caused by the fact that the reflection coefficient could be influenced not only by the overstory canopy but also by the forest floor. Thus, transmission coefficient was chosen as the indicator for the phenological changes in the following analysis. However, the transmission coefficient could not be directly used because extremely high or low values appeared during a day (e.g. Barr *et al.*, 2004; Yoshifuji *et al.*, 2006). The diurnal range of the transmission coefficient was especially large at this site (0.4–0.6) because of the following: (i) large spatial variation of the overstory canopy gaps because of the sparse stem density; and (ii) distinctive solar position in the high latitude (low solar elevation and wide range of solar azimuth). Therefore, the following screening procedure was conducted to detect the dates of leaf expansion and leaf fall. First, the transmission coefficients of solar radiation and PPFD at 30-minute interval were calculated. Then, the mean ( $\mu$ ) and standard deviation ( $\sigma$ ) for any five succeeding days were calculated, and the data that were less than  $\mu - \sigma$  or more

than  $\mu + \sigma$  were removed. With this screening procedure, the remaining transmission data showed a relatively clear seasonal trend. The dates of leaf phenological changes were determined using the daily maximum transmission coefficient of solar radiation between  $\mu - \sigma$  and  $\mu + \sigma$  as follows (Figure 1): the onset and completion of leaf expansion was defined as the day before the decreasing trend started and the day when the decreasing trend ended, respectively. The onset and completion of leaf fall were defined as the days before the increasing trend of transmission coefficient started and when the increasing trend ended, respectively. The canopy was considered to be fully foliated when the transmission coefficient had no clear temporal trend. At last, the dates of leaf expansion, fully foliated, and leaf fall periods were determined as shown in Figure 1. Note that the temporal variations of LAI could not be calculated on the basis of the transmission coefficient by the Beer–Lambert equation in this site (e.g. Jones, 1992). We only measured LAI once (August 2005), and therefore, the extinction coefficients of the equation for different seasons among the years were unavailable.

A complete description of the site and measurements is available in Ohta *et al.* (2008), Ishida (2009), and Xue *et al.* (2011).

#### Methods of analysis

We divided the measurement period of each year into three periods (Figure 1): the period before the latest completion date of leaf expansion over the four years (Period I; DOY = 121–164), the period between the latest completion date of leaf expansion and the earliest date of leaf fall over the four years (Period II; DOY = 164–253), and the period after the earliest date of leaf fall (Period III; DOY = 253–274). We examined the association between IAV in the  $E$  of each period and the IAV in the  $E$  measured during the whole measurement period (total  $E$ ).

Because we found that only the IAV in Period II was associated with the IAV in the total  $E$  (see the results), we thus investigated whether the IAV in  $E$  for Period II was related to the IAV in the equilibrium evaporation ( $E_{eq}$ ) for the same period. If this was not the case, the IAV in  $E$  for Period II should be positively correlated to the IAV in the Priestley–Taylor coefficient ( $\alpha$ , Priestley and Taylor, 1972)

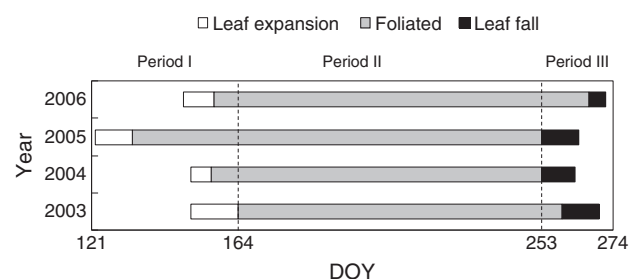


Figure 1. Leaf-expansion, foliated, and leaf fall periods in 2003–2006. Definition of Periods I–III also are indicated

because  $\alpha$  is defined as  $E$  divided by  $E_{eq}$ , and therefore,  $E$  must be positively correlated to either  $\alpha$  or  $E_{eq}$ . Here, we assumed that  $E_{eq}$  and  $\alpha$  are practically usable as indices for atmospheric demand and physiological control of the forest canopy, respectively. Forest  $E$  generally relates to VPD and surface conductance ( $G_s$ ) rather than  $E_{eq}$  and  $\alpha$  at the canopy scale, that is, forest canopies are generally coupled with the atmosphere (e.g. McNaughton and Jarvis, 1983; Herbst, 1995; Granier *et al.*, 2000). However, many researchers have shown that  $\alpha$  tightly correlates to  $G_s$  when considering the planetary boundary layer (PBL) feedback at a regional scale using PBL atmospheric models (de Bruin, 1983; McNaughton and Spriggs, 1986; Raupach, 1998). In the model calculation, VPD is produced by the temperature increment during daytime owing to the radiative energy ( $E_{eq}$ ), suggesting that  $E_{eq}$  correlates to VPD, and therefore, it can be practically used as an index for atmospheric demand. Consequently, many studies have used  $E_{eq}$  and  $\alpha$  for interpreting observational results for forest  $E$  (Baldocchi *et al.*, 1997, 2000; Wilson and Baldocchi, 2000; Vourlitis *et al.*, 2002; Komatsu, 2005) and for modeling forest  $E$  (Kumagai *et al.*, 2004; Komatsu *et al.*, 2007). Indeed, many observational studies reported correlation between  $\alpha$  and  $G_s$  for forest canopies (e.g. Baldocchi *et al.*, 1997, 2000; Wilson and Baldocchi, 2000; Arain *et al.*, 2003).

We finally examined whether  $E$  markedly increased in a specific period during Period II or displayed a constant increase throughout Period II. Similarly, we also examined whether SWC and  $\alpha$  were variable within the measurement periods of the same year.

In the analysis, we used  $E_{eq}$  and  $\alpha$  rather than VPD and  $G_s$  because the use of  $E_{eq}$  and  $\alpha$  is advantageous over the use of VPD and  $G_s$ ;  $E_{eq}$  and  $\alpha$  are usable at various time scales (e.g. daily, 10-day and monthly), whereas VPD and  $G_s$  are usable at only short time scales (e.g. hourly and daily). On the other hand, VPD and  $G_s$  are more direct and process-based parameters representing atmospheric demand and physiological control of  $E$  by forests. Thus, it would be important to confirm that our results did not change when using VPD and  $G_s$ . We calculated  $G_s$  for midday (10:00 h–14:00 h) using the inverted Penman–Monteith equation as (Jones, 1992):  $G_s^{-1} = \left( \frac{\Delta}{\gamma} \beta - 1 \right) G_a^{-1} + \frac{\rho_a c_p}{\lambda E \rho_w \gamma} VPD$ , where  $\Delta$  is the rate of change of saturation water vapor pressure with temperature ( $\text{Pa K}^{-1}$ ),  $\gamma$  is the psychrometric constant ( $66.5 \text{ Pa K}^{-1}$ ),  $G_a$  is the aerodynamic conductance ( $\text{m s}^{-1}$ ),  $\rho_a$  is the density of dry air ( $\text{kg m}^{-3}$ ),  $c_p$  is the specific heat of air at constant pressure ( $\text{J kg}^{-1} \text{K}^{-1}$ ),  $\lambda$  is the latent heat of vaporization of water ( $\text{J kg}^{-1}$ ),  $\rho_w$  is the density of water ( $1000 \text{ kg m}^{-3}$ ),  $\beta$  is the Bowen ratio (sensible heat flux divided by  $\lambda E$ ), and VPD is the above-canopy vapor pressure deficit (Pa).  $G_a$  was calculated by (e.g. Kumagai *et al.*, 2004):  $G_a = u_*^2 / u$ , where  $u_*$  is the friction velocity ( $\text{m s}^{-1}$ ), and  $u$  is wind speed ( $\text{m s}^{-1}$ ) measured at 32 m above the ground. All variables in the equation were averaged for midday and then input to the equation to obtain midday  $G_s$ .

## Results

Figure 2 shows the 10-day averages for daily net radiation, air temperature, VPD, and SWC, as well as cumulative precipitation and  $E$  during each year of the four-year periods. Net radiation was higher in Periods I and II than in Period III. Air temperature and VPD were generally higher in Period II than in Periods I and III. SWC increased during Period I, despite only a small amount of precipitation, which suggests that this was affected by melting water flux from the snow pack and frozen soil layer (Ohta *et al.*, 2008). SWC was relatively conservative in Periods II and III except for 2006, when there was a marked increase in SWC because of precipitation in late August. Precipitation mainly occurred during Period II, although the amount was relatively low in 2004. Cumulative  $E$  increased at a greater rate during Period II, reflecting the higher  $E$  during this period.

Over the four years, total  $E$  during May–September ranged between 156.1 and 206 mm (Figure 3a). The mean and standard deviation (SD) of  $E$  during May–September for the four years was 181.5 and 26.4 mm, respectively. Thus, the range and SD were 27.5% and 14.6% of the mean, respectively. This suggests that the IAV in total  $E$

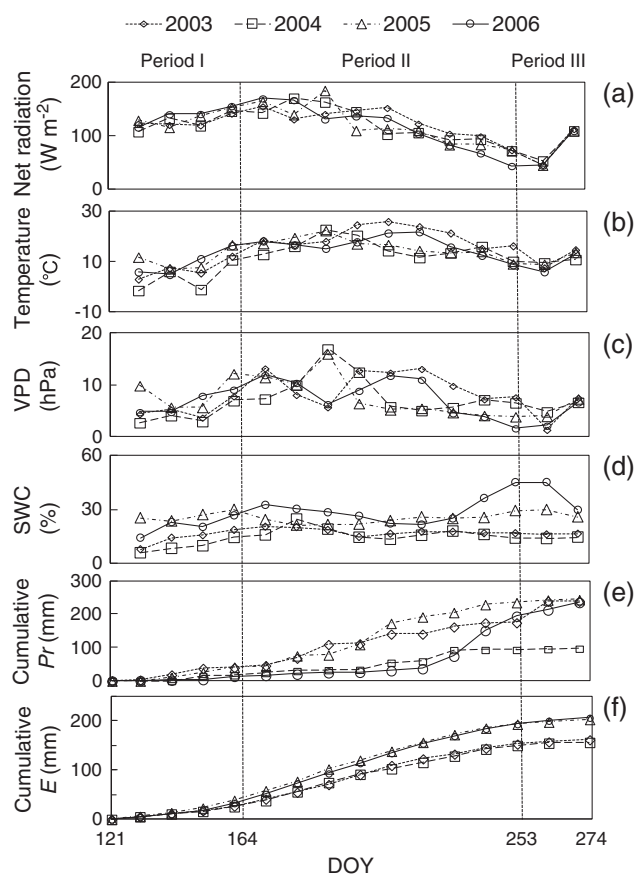


Figure 2. Time series of the environmental factors measured during the four years (2003–2006): 10-day averages of (a) net radiation, (b) air temperature, (c) vapor pressure deficit (VPD), and (d) soil water content (SWC), and cumulative (e) precipitation ( $Pr$ ) and (f) evapotranspiration ( $E$ ). Periods I–III also are indicated

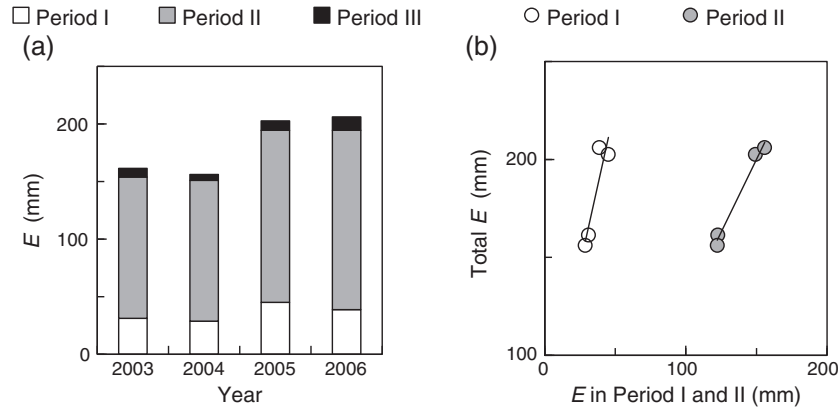


Figure 3. (a) Evapotranspiration ( $E$ ) in Periods I, II, and III, respectively. (b) Relationship between  $E$  in Period I (open circles) and Period II (closed circles) and the total  $E$  during May–September

was greater than the uncertainty of the flux measurements because the energy balance closure of the forest was relatively good (approximately 90%, Ohta *et al.*, 2008). The percentages for the range and SD were smaller than those for a deciduous old aspen forest in Canada but larger than those for evergreen forests of old black spruce and old jack pine (see Table 2 of Zha *et al.*, 2010). Thus, the IAV in total  $E$  at our site seemed moderate compared with these three boreal forests.

Total  $E$  was higher for 2005 and 2006 than for 2003 and 2004.  $E$  for Period II formed a larger proportion of total  $E$  than  $E$  for Periods I and III (Figure 3a). Total  $E$  was strongly correlated with  $E$  in Period II ( $p < 0.05$ ,  $r = 0.99$ , Figure 3b), indicating that the IAV in  $E$  in Period II was the primary cause for the IAV in total  $E$ . Indeed, the largest difference in total  $E$  was found between 2004 and 2006, and the difference in  $E$  during Period II of these two years explained 67% of the difference in total  $E$ . We also observed a weak, positive correlation between  $E$  for Period I and total  $E$  ( $p < 0.1$ ,  $r = 0.91$ ; Figure 3b), which suggests that the IAV in  $E$  during Period I was another cause for the IAV in total  $E$ . However, the slope of the relationship between  $E$  in Period I and total  $E$  was larger than that for  $E$  in Period II and total  $E$ , indicating that  $E$  in Period I was only a supplementary cause.

Based on the four-year dataset,  $E$  in Period II was not positively correlated with the  $E_{eq}$  of Period II ( $p > 0.1$ ), indicating that the IAV in  $E$  of Period II was not explained by IAV in the atmospheric demand for evaporation (Figure 4). This implied that IAV in  $E$  of Period II was decided by the physiological control ( $\alpha$ ). Values of  $\alpha$  in Period II were further correlated with SWC in Period II ( $p < 0.05$ ,  $r = 0.97$ ; Figure 5). These results suggest that the IAV in  $E$  for Period II was caused by the IAV in physiological control of  $E$  because of soil water deficit. In addition,  $\alpha$  in Period II was not correlated with air temperature in Period II ( $p > 0.1$ ,  $r = 0.47$ , data not shown).

The difference in cumulative  $E$  between the former two years and the latter two years constantly increased during Period II (Figure 2f), indicating that  $E$  was higher for the latter two years throughout Period II. Consistent

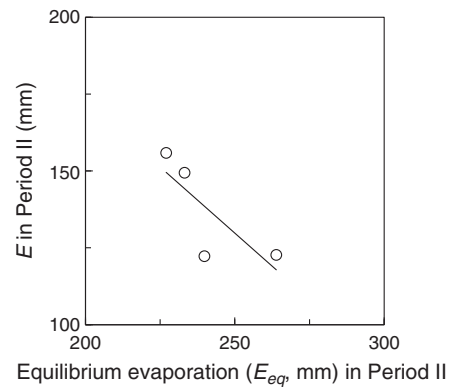


Figure 4. Relationship between equilibrium evaporation ( $E_{eq}$ ) and evapotranspiration ( $E$ ) in Period II. The regression line, determined using the least-squares method, is written as  $E = -0.86 E_{eq} + 344.74$  ( $R^2 = 0.62$ )

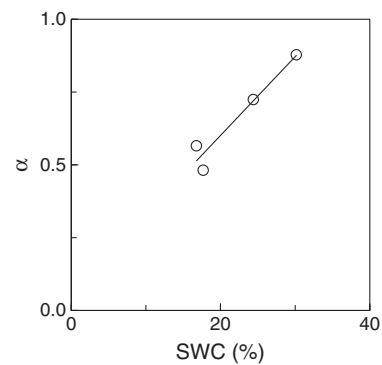


Figure 5. Relationship between SWC and the Priestley–Taylor coefficient ( $\alpha$ ). The regression line, determined using the least-squares method, is written as  $\alpha = 0.03 \text{ SWC} + 0.06$  ( $R^2 = 0.94$ )

with this, SWC and  $\alpha$  were generally higher during the latter two years than during the earlier two years throughout Period II (Figures 2 and 6). This shows that the IAV in total  $E$  was not caused by intermittent drought during Period II but by consistently lower SWC throughout Period II.

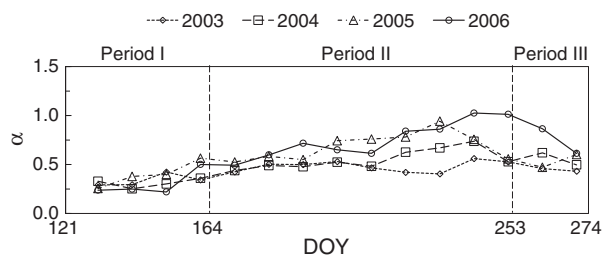


Figure 6. Time series of the Priestley–Taylor coefficient ( $\alpha$ ) calculated from 10-day average data for evapotranspiration and equilibrium evaporation data for the four years. Periods I–III also are indicated

The above results were not altered when using  $G_s$  and VPD instead of  $\alpha$  and  $E_{eq}$ . Figure 7a is the same as Figure 4 but using VPD instead of  $E_{eq}$ . We did not observe a positive correlation between VPD and  $E$  for Period II ( $p > 0.1$ ). On the other hand, we observed a positive correlation between the mean  $G_s$  for Period II and  $E$  for Period II ( $p < 0.05$ ,  $r = 0.95$ ; Figure 7b). We also observed  $G_s$  in Period II was further correlated with SWC in Period II ( $p < 0.05$ ,  $r = 0.96$ ; Figure 7c). Although we did not observe consistently higher  $G_s$  for 2005 and 2006 than 2003 and 2004 (data not shown) owing to the different VPD among years (Figure 2c), we observed consistently higher  $G_s$  for 2005 and 2006 than 2003 and 2004 for given VPD (Figure 7d). These results were qualitative, the same as those derived using  $\alpha$  and  $E_{eq}$ .

### Discussion

Although the IAV in the date of leaf expansion at our site was much more significant than those at temperate forests (Ishida, 2009), it was not the primary factor causing the IAV in total  $E$  of May–September. Atmospheric evaporative demand in Period I was relatively large;  $E_{eq}$  in Period I generally occupied approximately 25% of the total  $E_{eq}$  of May–September (data not shown). If  $\alpha$  in Period I was considerably affected by the date of leaf expansion, IAV in the date of leaf expansion could be a major factor determining the IAV in total  $E$ . In the present study, there was no evidence that  $\alpha$  in Period I was affected by the date of leaf expansion. Leaf expansion date in 2005 was the earliest among the four years, being around four weeks earlier than the other three years (Figure 1). However,  $\alpha$  in Period I was not much higher for this year than for the other years (Figure 6), suggesting relatively conservative  $\alpha$  despite the earlier date of leaf expansion. This might be partly explained by the presence of dense evergreen understory vegetation. Our previous study, using a multilayer canopy model, suggested that the LAI of the overstory greatly affects the partitioning of evaporative flux between overstory and understory vegetation but that it does not greatly affect the total evaporative flux of the ecosystem (Xue *et al.*, 2011).

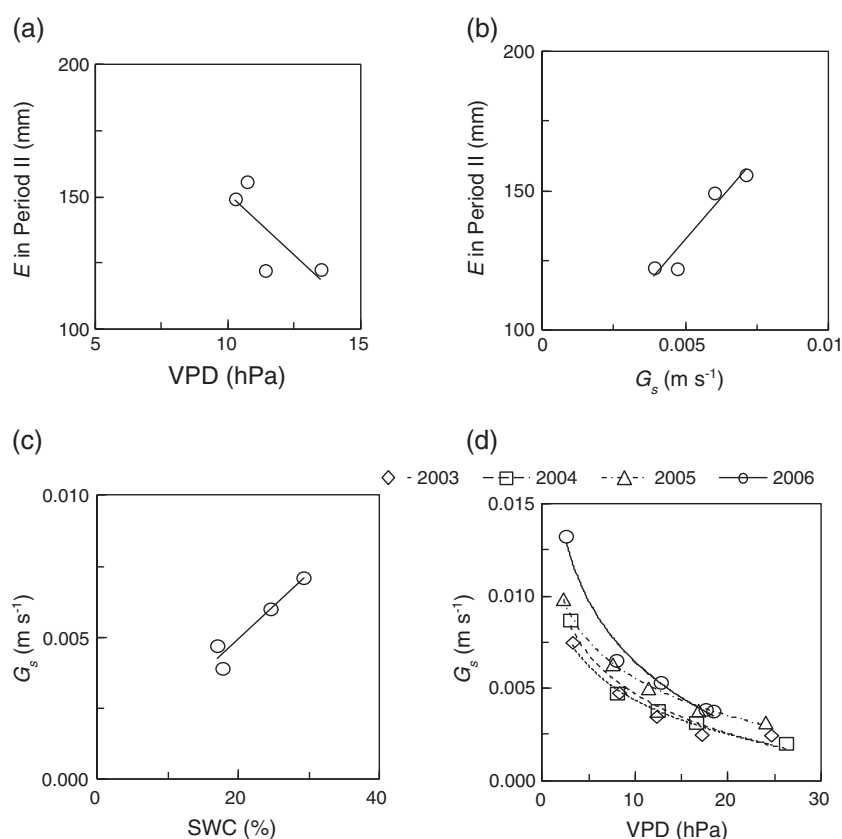


Figure 7. Relationships (a) between VPD and evapotranspiration ( $E$ ) in Period II, (b) between the mean surface conductance ( $G_s$ ) for Period II and  $E$  in Period II, (c) between SWC and  $G_s$ , and (d) between VPD and  $G_s$  for different VPD intervals.  $G_s$  data in Figure 7d are the means of  $G_s$  values for each VPD interval

Similarly, in the present study, the IAV in the date of leaf fall was not the primary factor driving the IAV in the total  $E$  during May–September. This was because atmospheric evaporative demand in Period III is small;  $E_{eq}$  in period III was approximately 5% of the total  $E_{eq}$  during May–September (data not shown).

There have been only a few studies examining the IAV in  $E$  for boreal forests, especially for boreal deciduous forests. The study by Zha *et al.* (2010) is an exception, examining the IAV in  $E$  for a boreal deciduous aspen forest in Canada. Their results are qualitatively the same as those of the present study; IAV in the date of leaf expansion was not the primary factor determining the IAV in total  $E$  of the measurement period (April–November for the study by Zha *et al.*) despite the presence of a considerable IAV in the date of leaf expansion (Barr *et al.*, 2004). Based on a nine-year dataset, Zha *et al.* (2010) reported a significant positive correlation between LAI and  $E$  in May, when leaf expansion generally occurred. This indicated that the IAV in the date of leaf expansion was one factor causing the IAV of the total  $E$  during their measurement period, but the data presented in their paper suggest that it was not the primary factor. The range (maximum–minimum) in the values of  $E$  in May for the nine years was approximately 40 mm (Figure 6 of Zha *et al.*, 2010), which was much lower than the range in the total  $E$  (241 mm according to Table 2 of Zha *et al.*). In fact, the data suggest that the IAV in  $E$  during the fully foliated period (June–September) was the primary factor determining the IAV in total  $E$ . According to their Figure 1, the IAV in the total  $E$  corresponded to that in  $\alpha$  during the fully foliated period.

$E$  (Figure 2f) and  $\alpha$  (Figure 6) for Period II were consistently higher for 2005 and 2006 than for 2003 and 2004, which corresponded to the higher SWC throughout Period II of 2005 and 2006. In our study site, there was relatively little fluctuation in the SWC during the foliated period (i.e. Period II) compared with that during Period I (Figure 1 d). This result contrasts with the results of previous studies examining the forest water cycle in temperate deciduous forest (Wilson and Baldocchi, 2000) and boreal deciduous forest (Zha *et al.*, 2010). In both these studies, the SWC fluctuated to a greater extent during the foliated period than before the period (Figure 2 of Wilson and Baldocchi, 2000; Figure 3 of Zha *et al.*, 2010). However, despite some precipitation, the SWC was not variable during Period II in our forest site (Figure 1 d). Two factors may partly explain this stability in SWC during Period II. First, the amount of precipitation was small (Figure 2e) compared with the amounts at the sites of these two studies. The mean precipitation in Period II during 2003–2006 was 175 mm at our site, whereas precipitation during May–October (generally corresponding to the foliated period) in the temperate deciduous forest was typically more than 500 mm (Figure 1 of Wilson and Baldocchi, 2000). Similarly, precipitation for June–August (generally corresponding to the foliated period) in Zha *et al.*'s boreal deciduous forest

was typically around 250 mm (Figure 1 of Blanken *et al.*, 2001). Second, the SWC in our forest site is affected by water flux from the permafrost as well as precipitation (Ohta *et al.*, 2008).

## Conclusions

In this study, we found that the IAV in the total  $E$  during the measurement period (May–September) was not primarily caused by the IAV in the dates of leaf expansion and leaf fall but instead by the IAV in  $E$  during the foliated period.  $E$  in the foliated period was consistently higher during years with higher  $E$ , corresponding to higher soil water content. Although there have been many studies examining IAV in the dates of leaf expansion and leaf fall and its effects on IAV in  $E$ , soil water content was found to be more important for understanding IAV in  $E$  at this site. As our conclusions are based on data from only four years, further studies using data collected over longer periods are required to confirm them. Our site is the only one where IAV in  $E$  has been examined for a larch forest in eastern Siberia; thus, we recommend further study of other forest sites in eastern Siberia to determine the generality of our results. This study can only be regarded as preliminary because we used above-canopy flux data, and therefore, we did not separate transpiration from the larch canopy and understory (note that soil evaporation would be negligible because of the dense understory), although there may be relatively high contribution of understory transpiration to total  $E$  (Iida *et al.*, 2009, Xue *et al.*, 2011). Thus, future studies should examine the IAV in transpiration from the larch canopy and understory and their correspondence to the IAV in soil water content.

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## References

- Arain MA, Black TA, Barr AG, Griffis TJ, Morgenstern K, Nesic Z. 2003. Year-round observations of the energy and water vapour fluxes above a boreal black spruce forest. *Hydrological Processes* 17: 3581–3600. DOI: 10.1002/hyp.1348.
- Baldocchi DD, Law BE, Anthoni PM. 2000. On measuring and modeling energy fluxes above the floor of a homogeneous and heterogeneous

- conifer forest. *Agricultural and Forest Meteorology* **102**: 187–206. DOI: 10.1016/S0168-1923(00)00098-8.
- Baldocchi DD, Vogel CA, Hall B. 1997. Seasonal variation of energy and water vapor exchange rates above and below a boreal jack pine forest canopy. *Journal of Geophysical Research-Atmospheres* **102**(D24): 28939–28951.
- Barr AG, Black TA, Hogg EH, Kljun N, Morgenstern K, Nesic Z. 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. *Agricultural and Forest Meteorology* **126**: 237–255. DOI:10.1016/j.agrformet.2004.06.011.
- Blanken PD, Black TA, Neumann HH, Den Hartog G, Yang PC, Nesic Z, Lee X. 2001. The seasonal water and energy exchange above and within a boreal aspen forest. *Journal of Hydrology* **245**: 118–136. DOI: 10.1016/S0022-1694(01)00343-2.
- Bonan GB. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320**: 1444–1449. DOI: 10.1126/science.1155121.
- Bonan GB, Chapin III FS, Thompson SL. 1995. Boreal forest and tundra ecosystems as components of the climate system. *Climatic Change* **29**: 145–167. DOI: 10.1007/BF01094014.
- Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61. DOI: 10.1016/j.jhydrol.2004.12.010.
- Cienciala E, Running SW, Lindroth A, Grelle A, Ryan MG. 1998. Analysis of carbon and water fluxes from the NOPEX boreal forest: comparison of measurements with FOREST-BGC simulations. *Journal of Hydrology* **212–213**: 62–78. DOI: 10.1016/S0022-1694(98)00202-9.
- De Bruin HAR. 1983. A model for the Priestley-Taylor parameter alpha. *Journal of Climate and Applied Meteorology* **22**: 572–578. DOI: 10.1175/1520-0450(1983)022 <0572:AMFTPT > 2.0.CO;2.
- Food and Agriculture Organization of the United Nations. 2005. State of the World's Forests. Rome: Food and Agriculture Organization of the United Nations, Forest Department.
- Granier A, Biron P, Lemoine D. 2000. Water balance, transpiration and canopy conductance in two beech stands. *Agricultural and Forest Meteorology* **100**: 291–308. DOI: 10.1016/S0168-1923(99)00151-3.
- Granier A, Pilegaard K, Jensen NO. 2002. Similar net ecosystem exchange of beech stands located in France and Denmark. *Agricultural and Forest Meteorology* **114**: 75–82. DOI: 10.1016/S0168-1923(02)00137-5.
- Grelle A, Lindroth A, Mölder M. 1999. Seasonal variation of boreal forest surface conductance and evaporation. *Agricultural and Forest Meteorology* **98–99**: 563–578. DOI: 10.1016/S0168-1923(99)00124-0.
- Halldin S, Gryning SE, Gottschalk L, Jochum A, Lundin LC, Van De Griend AA. 1999. Energy, water and carbon exchange in a boreal forest landscape - NOPEX experiences. *Agricultural and Forest Meteorology* **98–99**: 5–29. DOI: 10.1016/S0168-1923(99)00148-3.
- Herbst M. 1995. Stomatal behaviour in a beech canopy: an analysis of Bowen ratio measurements compared with porometer data. *Plant, Cell & Environment* **18**: 1010–1018. DOI: 10.1111/j.1365-3040.1995.tb00611.x.
- Horst TW, Weil JC. 1992. Footprint estimation for scalar flux measurements in the atmospheric surface layer. *Boundary-Layer Meteorology* **59**: 279–296. DOI: 10.1007/BF00119817.
- Horst TW, Weil JC. 1994. How far is far enough? The fetch requirements for micrometeorological measurement of surface fluxes. *Journal of Atmospheric & Oceanic Technology* **11**: 1018–1025. DOI: 10.1175/1520-0426(1994)011 <1018:HFIFET > 2.0.CO;2 DOI: dx.doi.org
- Hui D, Wan S, Su B, Katul G, Monson R, Luo Y. 2004. Gap-filling missing data in eddy covariance measurements using multiple imputation (MI) for annual estimations. *Agricultural and Forest Meteorology* **121**: 93–111. DOI: 10.1016/S0168-1923(03)00158-8.
- Iida S, Ohta T, Matsumoto K, Nakai T, Kuwada T, Kononov AV, Maximov TC, van der Molen MK, Dolman H, Tanaka H, Yabuki H. 2009. Evapotranspiration from understory vegetation in an eastern Siberian boreal larch forest. *Agricultural and Forest Meteorology* **149**: 1129–1139. DOI: 10.1016/j.agrformet.2009.02.003.
- Ishida M. 2009. Effects of phenological variations on evapotranspiration (In Japanese with English summary). *Graduate School of Bioagricultural Sciences*. Nagoya: Nagoya University.
- Jarvis PG, Saugier B, Schulze E-D. 2001. Productivity of Boreal Forests, In *Terrestrial Global Productivity*, Roy BJS, Mooney HA (eds). Academic Press: San Diego; 211–244.
- Jones HG. 1992. *Plants and Microclimate*. Cambridge University Press: Cambridge.
- Kelliher FM, Hollinger DY, Schulze ED, Vygodskaya NN, Byers JN, Hunt JE, McSeveny TM, Milukova I, Sogatchev A, Varlargin A, Ziegler W, Arneth A, Bauer G. 1997. Evaporation from an eastern Siberian larch forest. *Agricultural and Forest Meteorology* **85**: 135–147. DOI: 10.1016/S0168-1923(96)02424-0.
- Kelliher FM, Lloyd J, Arneth A, Byers JN, McSeveny TM, Milukova I, Grigoriev S, Panfyorov M, Sogatchev A, Varlargin A, Ziegler W, Bauer G, Schulze ED. 1998. Evaporation from a central Siberian pine forest. *Journal of Hydrology* **205**: 279–296. DOI: 10.1016/S0022-1694(98)00082-1.
- Komatsu H. 2005. Forest categorization according to dry-canopy evaporation rates in the growing season: comparison of the Priestley-Taylor coefficient values from various observation sites. *Hydrological Processes* **19**: 3873–3896. DOI: 10.1002/hyp.5987.
- Komatsu H, Kume T, Otsuki K. 2008. The effect of converting a native broad-leaved forest to a coniferous plantation forest on annual water yield: A paired-catchment study in northern Japan. *Forest Ecology and Management* **255**: 880–886. DOI: 10.1016/j.foreco.2007.10.010.
- Komatsu H, Kume T, Otsuki K. 2011. Increasing annual runoff-broadleaf or coniferous forests? *Hydrological Processes* **25**: 302–318. DOI: 10.1002/hyp.7898.
- Komatsu H, Tanaka N, Kume T. 2007. Do coniferous forests evaporate more water than broad-leaved forests in Japan? *Journal of Hydrology* **336**: 361–375. DOI: 10.1016/j.jhydrol.2007.01.009
- Kumagai T, Saitoh TM, Sato Y, Morooka T, Manfroi OJ, Kuraji K, Suzuki M. 2004. Transpiration, canopy conductance and the decoupling coefficient of a lowland mixed dipterocarp forest in Sarawak, Borneo: Dry spell effects. *Journal of Hydrology* **287**: 237–251. DOI: 10.1016/j.jhydrol.2003.10.002.
- Kumagai T, Tateishi M, Shimizu T, Otsuki K. 2008. Transpiration and canopy conductance at two slope positions in a Japanese cedar forest watershed. *Agricultural and Forest Meteorology* **148**: 1444–1455. DOI: 10.1016/j.agrformet.2008.04.010.
- Matsumoto K, Ohta T, Nakai T, Kuwada T, Daikoku K, Iida S, Yabuki H, Kononov AV, van der Molen MK, Kodama Y, Maximov TC, Dolman AJ, Hattori S. 2008. Energy consumption and evapotranspiration at several boreal and temperate forests in the Far East. *Agricultural and Forest Meteorology* **148**: 1978–1989. DOI: 10.1016/j.agrformet.2008.09.008.
- McCaughy JH, Lafleur PM, Joiner DW, Bartlett PA, Costello AM, Jelinski DE, Ryan MG. 1997. Magnitudes and seasonal patterns of energy, water, and carbon exchanges at a boreal young jack pine forest in the BOREAS northern study area. *Journal of Geophysical Research D: Atmospheres* **102**: 28997–29007. DOI: 10.1029/97JD00239.
- McNaughton KG, Jarvis PG. 1983. Predicting effects of vegetation changes on transpiration and evaporation. In *Water deficits and plant growth*, vol. VII, Kozlowski TT (ed.). Academic Press: New York; 1–47.
- McNaughton KG, Spriggs TW. 1986. A mixed-layer model for regional evaporation. *Boundary-Layer Meteorology* **34**: 243–262. DOI: 10.1007/BF00122381.
- Miyahara M. 2005. Responses of boreal vegetation to soil moisture (In Japanese with English summary). Nagoya University.
- Mkhabela MS, Amiro BD, Barr AG, Black TA, Hawthorne I, Kidston J, McCaughy JH, Orchansky AL, Nesic Z, Sass A, Shashkov A, Zha T. 2009. Comparison of carbon dynamics and water use efficiency following fire and harvesting in Canadian boreal forests. *Agricultural and Forest Meteorology* **149**: 783–794. DOI: 10.1016/j.agrformet.2008.10.025.
- Nakai T, Sumida A, Daikoku K, Matsumoto K, van der Molen MK, Kodama Y, Kononov AV, Maximov TC, Dolman AJ, Yabuki H, Hara T, Ohta T. 2008. Parameterisation of aerodynamic roughness over boreal,



- cool- and warm-temperate forests. *Agricultural and Forest Meteorology* **148**: 1916–1925. DOI: 10.1016/j.agrformet.2008.03.009.
- Ohta T, Hiyama T, Tanaka H, Kuwada T, Maximov TC, Ohata T, Fukushima Y. 2001. Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. *Hydrological Processes* **15**: 1459–1476. DOI: 10.1002/hyp.219.
- Ohta T, Maximov TC, Dolman AJ, Nakai T, van der Molen MK, Kononov AV, Maximov AP, Hiyama T, Iijima Y, Moors EJ, Tanaka H, Toba T, Yabuki H. 2008. Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). *Agricultural and Forest Meteorology* **148**: 1941–1953. DOI: 10.1016/j.agrformet.2008.04.012.
- Pejam MR, Arain MA, McCaughey JH. 2006. Energy and water vapour exchanges over a mixedwood boreal forest in Ontario, Canada. *Hydrological Processes* **20**(17): 3709–3724. DOI: 10.1002/hyp.6384.
- Priestley CHB, Taylor RJ. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* **100**: 81–92.
- Raupach MR. 1998. Influences of local feedbacks on land-air exchanges of energy and carbon. *Global Change Biology* **4**: 477–494.
- Sellers P. 1995. The Boreal Ecosystem-Atmosphere Study (BOREAS): an overview and early results from the 1994 field year. *Bulletin of the American Meteorological Society* **76**: 1549–1577. DOI: 10.1175/1520-0477(1995)076 < 1549:TBESAO > 2.0.CO;2 DOI: dx.doi.org.
- Sellers PJ, Hall FG, Kelly RD, Black A, Baldocchi D, Berry J, Ryan M, Ranson KJ, Crill PM, Lettenmaier DP, Margolis H, Cihlar J, Newcomer J, Fitzjarrald D, Jarvis PG, Gower ST, Halliwell D, Williams D, Goodison B, Wickland DE, Guertin FE. 1997. BOREAS in 1997: Experiment overview, scientific results, and future directions. *Journal of Geophysical Research D: Atmospheres* **102**: 28731–28769. DOI: 10.1029/97JD03300.
- Vourlitis GL, Priante Filho N, Hayashi MMS, Nogueira JDS, Caseiro FT, Campelo Jr JH. 2002. Seasonal variations in the evapotranspiration of a transitional tropical forest of Mato Grosso, Brazil. *Water Resources Research* **38**: 1094. DOI: 10.1029/2000WR000122.
- Webb, EK, Pearman, GI, Leuning, R. 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society* **106**: 85–100. DOI: 10.1002/qj.49710644707.
- Wilson KB, Baldocchi DD. 2000. Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. *Agricultural and Forest Meteorology* **100**: 1–18. DOI: 10.1016/S0168-1923(99)00088-X.
- Xue B-L, Kumagai T, Iida S, Nakai T, Matsumoto K, Komatsu H, Otsuki K, Ohta T. 2011. Influences of canopy structure and physiological traits on flux partitioning between understory and overstory in an eastern Siberian boreal larch forest. *Ecological Modeling* **222**: 1479–1490. DOI: 10.1016/j.ecolmodel.2011.01.021.
- Yoshifuji N, Kumagai T, Tanaka K, Tanaka N, Komatsu H, Suzuki M, Tantasirin C. 2006. Inter-annual variation in growing season length of a tropical seasonal forest in northern Thailand. *Forest Ecology and Management* **229**: 333–339.
- Zha T, Barr AG, van der Kamp G, Black TA, McCaughey JH, Flanagan LB. 2010. Interannual variation of evapotranspiration from forest and grassland ecosystems in western Canada in relation to drought. *Agricultural and Forest Meteorology* **150**: 1476–1484. DOI: 10.1016/j.agrformet.2010.08.003.