

Estimation of vertical profiles of leaf drying times after daytime rainfall within a Bornean tropical rainforest

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Abstract:

South-east Asian Bornean tropical rainforests have large and complex canopy structures. To clarify how forest structure affects wet-canopy evaporation, it is necessary to consider wet-canopy evaporation processes within the forest canopy, such as vertical profiles of canopy drying time. In a previous study a method was proposed that utilizes sap flow measurements to estimate canopy drying time after rainfall (CDTobs) during daytime. In this present study, the method was applied to estimations of the vertical variations in CDTobs in 11 individual trees of various heights, ranging from 2.7 m to 53 m. The study derived vertical profiles and showed that the lengths of CDTobs in lower canopy trees were 2–4 h longer than those in the upper canopy trees. The new method for CDTobs profiles presented in this study, which is available for validation of multi-layer biosphere-atmospheric models, is a useful illustration for clarifying wet-canopy evaporation processes in tropical rainforests. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS sap flow; wet canopy evaporation; canopy drying time; multi-layer model

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INTRODUCTION

Tropical rainforests are a major latent energy source, having an influence on global and regional water cycling (Lean and Warrilow, 1989; Kanae *et al.*, 2001; Mabuchi *et al.*, 2005). In tropical forests in south-east Asia, where the relative deforestation rates are among the world's highest (Houghton and Hackler, 1999; Malhi and Grace, 2000), predicting the consequences of land-use changes for evapotranspiration is a critical issue. Evapotranspiration has two quite different aspects that depend on whether the canopy is wet or dry; wet- and dry-canopy evaporation. In terms of water cycling in tropical forest ecosystems, because of the large amount of rainfall involved, wet-canopy evaporation is a hydrologic component of major importance in determining the water budget of forest areas (Jackson, 1975; Lloyd *et al.*, 1988; Scatena, 1990; Jetten, 1996; Dykes, 1997; Asdak *et al.*, 1998; Schellekens *et al.*, 2000; Kuraji and Tanaka, 2003; Manfroi *et al.*, 2006). Therefore, measurements and models of wet-canopy evaporation are needed to clarify the effects on water cycling in this region for land use.

Tropical rainforests in south-east Asia are characterized by a complex canopy structure because of the diversity of tree species and tall emergent trees, some of which are taller than 70 m (Kira, 1978; Whitmore, 1994). This results in strong vertical gradients of micro-meteorological factors such as solar radiation, humidity, and wind speed within a forest canopy (Kumagai *et al.*, 2001). Such vertical gradients can affect the total amount of wet-canopy evaporation, or the duration of wet-canopy evaporation (Watanabe and Mizutani, 1996). One-dimensional multi-layer biosphere-atmospheric models (multi-layer models) are promising tools for understanding how forest structure impacts on wet-canopy evaporation. By using multi-layer models, vertical variations in wet-canopy evaporation have been reproduced in some studies conducted in temperate forests (Watanabe and Mizutani, 1996; Takanashi *et al.*, 2003; Tanaka K, 2002; Park and Hattori, 2004). However, to the authors' knowledge, there are no studies examining wet-canopy evaporation processes within a forest canopy in a tropical rainforest using multi-layer models. In addition, many multi-layer models have been developed to reproduce biosphere-atmospheric CO₂ and H₂O exchange under dry-canopy conditions (Williams *et al.*, 1998; Lai *et al.*, 2000; Baldocchi and Wilson, 2001; Kumagai *et al.*, 2006).

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To reproduce wet-canopy evaporation using multi-layer models, a prerequisite is measurements of wet-canopy evaporation processes. In previous studies, latent heat fluxes measured by an eddy covariance method (Watanabe and Mizutani, 1996; Williams *et al.*, 1998; Baldocchi and Wilson, 2001; Tanaka *et al.*, 2003; Takanashi *et al.* 2003), and net rainfall measurements based on event measurements of throughfall and stem-flow (Tanaka *et al.*, 2003) have been used to validate multi-layer models. In a recent study, vertical profiles of canopy drying time (or wet canopy duration) after rainfall within a forest canopy, which is the period required to dry out a canopy exposed to rainfall, were successfully used as validation data for a multi-layer model (Takanashi *et al.*, 2003). Neglecting canopy drying time after rainfall within a forest canopy as part of the validation data could cause serious errors in reproducing wet- and dry-canopy evaporation, especially in tropical rainforests where short rain events occur frequently (Lloyd *et al.*, 1988; Noguchi *et al.*, 2003; Manfroi *et al.*, 2006). However, the vertical variations in canopy drying time after rainfall within a forest canopy have never been shown in tropical rainforests, because of the large and complex canopy structure, and the lack of a facility to carry out measurements (Kume *et al.*, 2006).

This study was undertaken to illustrate measurements of vertical variations in canopy drying time, and to clarify the characteristics of vertical variations in canopy drying time after rainfall within a tropical rainforest canopy. To achieve this, vertical variations in canopy drying time after rainfall within a forest canopy were estimated from sap flow measurements conducted in individual trees of various heights, ranging from 2.7 m to 53 m, in a Bornean tropical rainforest. Canopy drying time after rainfall has usually been detected by wetness sensors (Lindroth, 1993; Takanashi *et al.*, 2003). However, this study used sap flow measurements as a detector of canopy wetness, because sap flows, which decrease during canopy wetting, can provide information about integrated leaf wetness conditions throughout the entire canopy of a tree (Bosveld and Bouten, 2003; Takanashi *et al.*, 2003; Kajitani *et al.*, 2005; Kume *et al.*, 2006). In addition, since a sensor for sap flow measurements can be installed at an accessible point, the method used has advantages over the use of wetness sensors that require special platforms for measurements.

MATERIALS AND METHODS

Site

This study was carried out in a lowland mixed-dipterocarp forest in the Lambir Hills National Park, Sarawak, Malaysia (4°20'N, 113°50'E), situated approximately 30 km southwest of Miri, Sarawak. The mean annual temperature at Miri airport, 20 km from the study site, is approximately 27 °C, with small seasonal fluctuations, and the mean annual rainfall for the period

1968–2001 was approximately 2700 mm with some seasonal variation (Kumagai *et al.*, 2005; Gomyo and Kuraji, 2006). Rainfall measurements, which commenced in January 1999 in this park, show that rainfall is composed of relatively more intense storms that occur between 1 and 4 pm, and less intense but longer duration storms occurring between 9 pm and 6 am (Kume *et al.*, 2006; Manfroi *et al.*, 2006). Most rain events in this park can be divided into two types; afternoon rainfall around an afternoon peak, and midnight rainfall around a midnight peak

In this park, a 93 m tall crane facility and a 49.5 m tree tower have been constructed for long-term ecohydrological studies (Nakashizuka *et al.*, 2001; Ozanne *et al.*, 2003). Measurements in this study were mainly conducted in the area surrounding the crane, a 4 ha study plot divided into 400 subplots (10 m × 10 m square grid). Sap flow measurements and an inventory of all trees with a diameter at breast height >1 cm reported here were carried out in one of the subplots. To include sufficient samples of emergent trees, some sap flow measurements were carried out around the tree tower, which is located approximately 540 m south-west of the crane.

Forest structure

The Park has an area of 6949 ha, 85% of which is covered by the lowland mixed-dipterocarp forest that is common in Borneo (Yamakura *et al.*, 1995; Itoh *et al.*, 1997; Condit *et al.*, 2000). It has a continuous canopy height of approximately 50 m. All trees with a diameter at breast height (DBH) >1 cm in a subplot were measured for DBH, tree height, the height to the first living branch, and the species was identified. The mean density of trees with DBH >1 cm was 6500 trees ha⁻¹, of which about 90% had DBH <10 cm, and the mean density of trees with DBH >10 cm was 700 trees ha⁻¹. Mean total basal area was 43.3 m² ha⁻¹. A more complete description of the lowland tropical rainforest is available in Nakagawa *et al.* (2000) and Manfroi *et al.* (2004).

The leaf area index (LAI) was measured using a pair of plant canopy analysers (LAI-2000, Li-Cor, Lincoln, Nebraska, USA) every 5 m on a 30 × 30 m² subplot. The LAI ranged spatially from 4.8 to 6.8 m² m⁻² with a mean of 6.2 m² m⁻² (Kumagai *et al.*, 2004). Vertical variations in LAI were also measured at 5 m intervals along four vertical observation lines using the crane facility and the pair of plant canopy analysers (Kumagai *et al.* 2006). The accumulated LAI data measured from the top of the canopy to the forest floor showed that leaves were distributed evenly within the canopy (Figure 1). In this study, all trees in a subplot were categorized into four levels according to Kira (1978). The four categories of tropical forest canopy were designated depending on the canopy position as follows; a first layer of emergent trees, a second layer of the crowns of large trees, a third layer of the crowns of small trees, and a fourth layer of shrub (Figure 1). This study assumed that the canopy position could be a primary factor influencing the leaf drying time of each tree because of the strong vertical gradients of

meteorological conditions within the forest canopy at this site (Kumagai *et al.*, 2001). Two to four trees in each canopy level were selected for sap flow measurements regardless of tree species (Table I).

Sap flow measurements

This study used the diurnal variation in sap flow velocities in individual trees as a detector of canopy wetness. Sap flow measurements were conducted using the thermal heat-pulse method (Closs, 1958; Marshall, 1958) in 11 sample trees (Table I) from August 2004 through October 2004. A heat pulse sensor (HP-1, Hayasi Denko, Tokyo, Japan) containing a heater probe and two thermistor probes (2.0 mm in diameter, 50 mm in length) was used. The heater probe was inserted radially into the stem at a height above the buttress in emergent trees in canopy level 1 and at about 1 m height above the ground in individuals in canopy levels 2, 3, and 4 (Table I). The two thermistor probes were vertically aligned asymmetrically around the heater probe. The upper and lower probes were spaced 10 and 7 mm, respectively, from the heater probe. The sensors were

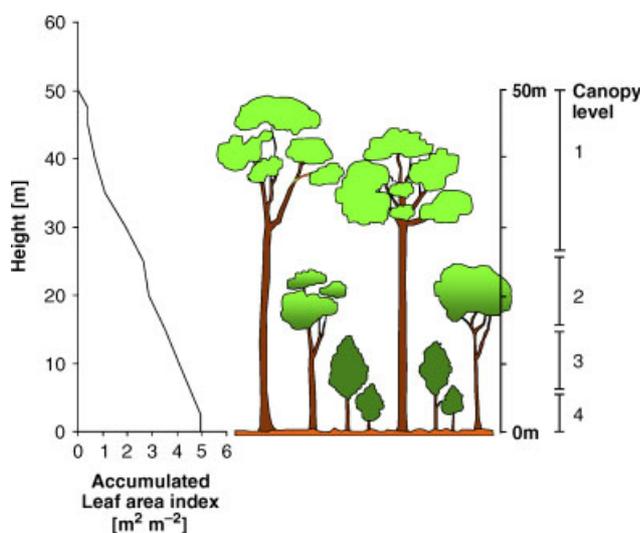


Figure 1. (a) Vertical distribution of the leaf area index determined by one vertical observation line; after Kumagai *et al.* (2006). (b) Schematic representation of the sample trees; categorized into four levels depending on canopy position

installed in holes drilled with a gauge guide into the outer xylem to a depth at which the sap flow velocity peaked in the radial profiles. A heat-pulse tracer was released for 1.5 s every 20 min, and the heat pulse velocity was stored in a data logger (CR10X, Campbell Scientific, Logan, UT, USA). To account for the influence of sap flow interruption around an implanted sensor, the heat pulse velocity was adjusted to the sap flow velocity using Swanson's method (Swanson and Whitfield, 1981; Kominami and Suzuki, 1993).

Time lags between canopy transpiration and basal sap flow more than the measurement interval (i.e. 20 min) were insignificant when sap flow velocities in a branch at 50 m height and a stem above the buttresses were measured in *Dryobalanops aromatica*. Cross-correlation analysis showed strong correlation between branch and stem sap flow velocities in *D. aromatica* ($r = 0.98$ at zero time lag) (Kume *et al.*, 2007a), and also among the stem sap flow velocities measured in the 50 m tall emergent trees (mean $r = 0.96$ at zero time lag). Furthermore, it has been reported that time lags between canopy transpiration and stem sap flows decreased with decreases in tree size in a neo-tropical forest (Goldstein *et al.*, 1998). These results mean that the time lag between canopy transpiration and sap flow in a stem owing to internal water storage and hydraulic resistance (Landsberg *et al.*, 1976; Phillips *et al.*, 1997; Kumagai, 2001) was negligible at this site and that almost the same diurnal variations in sap flow velocities would be obtained regardless of differences in the sensor positions for the sample trees. However, some studies have reported remarkable time lags in a tropical evergreen forest (Phillips *et al.*, 1999; Goldstein *et al.*, 1998).

Meteorological measurements

Solar radiation was sampled every 5 s using a solar radiometer (MS401, EKO, Tokyo, Japan), and an averaging period of 10 min was used (CR10X data logger, Campbell Scientific, Logan, UT, USA). Rainfall was measured using a tipping bucket rain gauge (20 cm in diameter and 0.5 mm in tip resolution; RS102, Ogasawara Keiki, Tokyo, Japan) and its tip timing was

Table I. Characteristics of sample trees selected for sap flow measurements

Family	Species	Height [m]	Stem diameter [cm]	Lowest crown's height [m]
Dipterocarpaceae	<i>Dryobalanops aromatica</i>	53.4	142.7	34.9
Dipterocarpaceae	<i>Shorea beccariana</i>	51.3	97.5	38.6
Dipterocarpaceae	<i>Dipterocarpus pachyphyllus</i> *	49.2	113.1	31.2
Moraceae	<i>Ficus crassiramea</i> *	45.7	17.8	31.2
Loganiaceae	<i>Fagraea caudata</i>	42.5	131.1	20.9
Dipterocarpaceae	<i>Shorea laxa</i>	18.5	13.8	5.2
Dipterocarpaceae	<i>Shorea acuta</i>	18.5	19.1	7.0
Euphorbiaceae	<i>Beccaurea sarawakensis</i>	12.0	10.1	7.8
Oxalidaceae	<i>Sarcotheca xanthophyllum</i>	10.0	7.0	4.8
Ebenaceae	<i>Diospyros pendula</i>	5.2	3.6	1.6
Burseraceae	<i>Dacryodes rostrata</i>	2.7	1.4	0.5

* Sample tree located at the crane site about 540 m south-west of the subplot.

recorded with a data logger (HOBO event, Onset Computer, Bourne, MA). These measurements were conducted at 85.8 m on the crane. Air temperature and humidity, measured using a thermohygrograph (HMP45, Vaisala, Helsinki, Finland), were recorded at 10 min intervals with a data logger (SQ1250, Cambridge, UK) at 76.3 m on the crane. At the same height, wind speed was sampled every 5 s using a three-cup anemometer (AC750, Makino, Tokyo, Japan), and an averaging period of 10 min was used (CR10X).

Definition of canopy drying time

Transpiration from whole or partially wet leaves is lower than that from completely dry leaves because atmospheric evaporative energy is consumed by wet-canopy evaporation in addition to transpiration (Rutter *et al.*, 1975; Watanabe and Mizutani, 1996; Bosveld and Bouten, 2003). The decrease in transpiration due to canopy wetting can be monitored continuously by sap flow measurements (Bosveld and Bouten, 2003; Takanashi *et al.*, 2003; Kajitani *et al.*, 2005). In a previous study, canopy drying time after rainfall was defined from sap flow velocities (Kume *et al.*, 2006).

At this site, when sap flow velocity after rainfall becomes equal to the value of the sap flow velocity assumed for bright days, it can be assumed that the effect of leaf wetness on transpiration is removed and that the canopy is completely dry. Sap flow velocity measured at the same time on bright days can have almost the same value throughout the year at this aseasonal site; thus, sap flow velocity that is lower than expected after rainfall on a bright day is thought to be due to the canopy wetness at this site, where cloudy weather after rainfall tends to abruptly change to sunny (Kume *et al.*, 2006).

Figure 2 shows the diurnal variations in the sap flow velocity averaged over 10 bright days with standard deviation, and the sap flow velocity for a rainy day as well as during the actual rainfall. In a previous study, estimated canopy drying time by sap flow velocities (CDT_{Obs}) was defined as follows (a more complete background and practical limitation of the CDT_{Obs} is available in Kume *et al.* (2006)):

$$CDT_S \leq CDT_{Obs} \leq CDT_L, \quad (1)$$

where CDT_S is defined as the period from the time rain ceased (A) to a specific time S , CDT_L is defined as the period from A to a specific time L , S is the time when sap flow velocity after rainfall exceeds the average minus the standard deviation of the sap flow velocity averaged over 10 bright days, and L is the time when the sap flow velocity after rainfall exceeds the average of the sap flow velocity averaged over 10 bright days. This study assumes that the wet canopy dries out in the period from S to L , and that CDT_{Obs} is defined as ranging between CDT_S and CDT_L at each rain event. The bright days selected in this study were the top 10 days showing larger daily solar radiations in the measurement period without rain. The diurnal variations in the sap

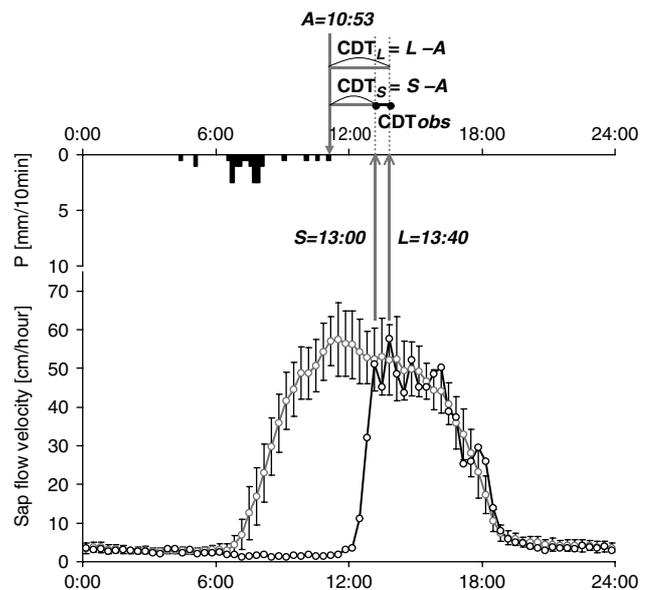


Figure 2. Definition of estimated canopy drying time after rainfall (CDT_{Obs}) after Kume *et al.* (2006). (a) Rainfall (P); (b) diurnal courses of sap flow velocity during a rainy (black line) period and the average over 10 bright days (gray line). Vertical bars indicate standard deviation. CDT_S and CDT_L , A , S , L are detailed in the text

flow velocity averaged over these 10 bright days were calculated for each tree. Although the '10 days' was itself an arbitrary number, it was confirmed that the average and the standard deviation of the sap flow velocities averaged over more than 10 days were almost same as the values averaged over 10 days. Consequently, in the case of the rain event in Figure 2, CDT_S and CDT_L are defined as 127 min and 167 min, respectively, while CDT_{Obs} is defined as the range between 127 and 167 min.

In this study, three criteria were used to select target rain events to derive CDT_{Obs} : (1) Rainfall ceased in the daytime from 06:00 to 17:00. (2) The period of no rainfall between each rain event exceeded 2 h. (3) Total rainfall for each rain event exceeded a threshold of 1.5 mm. There are two reasons for the three criteria; sap flow occurs during the daytime, and the studied canopy needs to be fully wet at the time rainfall ceases. The thresholds of 1.5 mm and no-rain periods of 2 h or less were to ensure enough rainwater to guarantee a fully wet canopy at the time rainfall ceased (Lloyd *et al.*, 1988; Jetten *et al.*, 1996; Dykes, 1997; Schellekens *et al.*, 2000; Manfroi *et al.*, 2004).

RESULTS

Typical diurnal variations in sap flow velocities measured in sample trees in each canopy level are shown in Figure 3 with diurnal variations in rainfall. The commencement of sap flow velocities in canopy levels 2, 3, and 4 (0–20 m from the ground) after rainfall lagged behind those in canopy level 1 (30–50 m from the ground). When afternoon rainfall occurred, the time lag of the commencement of sap flow velocities after rainfall between canopy level 1 and 2, 3, and 4 spanned 1–2 h

(Figure 3b). When preceding midnight rainfall occurred, the time lag of the commencement of sap flow velocities between canopy level 1 and 2, 3, and 4 spanned 2–3 h in the morning (Figure 3c). When preceding midnight rainfall was not observed, the time lags between canopy levels in the morning were less distinctive than when preceding midnight rainfall occurred (Figure 3a). This indicated that the time lags of the commencement of sap flow velocities after rainfall between upper and lower canopy trees are caused by the differences in micro-meteorological conditions, such as solar radiation, humidity, and wind speed, and differences in canopy drying time after rainfall between the upper and lower canopies.

Figure 4 shows the vertical profiles of canopy drying time after rainfall by sap flow measurements (CDT_{obs}) for four rain events satisfying the three criteria; CDT_{obs} in canopy level 1 were shorter than those in canopy levels 2, 3, and 4. In the case of afternoon rainfall on 24 and 31 August, CDT_{obs} in canopy level 1 distributed around 2 h, while CDT_{obs} in canopy levels 2, 3, and 4 distributed in a range between 2 and 4 h. In the case of midnight rainfall on 11 and 25 September, CDT_{obs} in canopy level 1 distributed around 4 h, while, CDT_{obs} in canopy levels 2, 3, and 4 distributed in a range between 6 and 8 h. In both types of rain event, the lengths of CDT_{obs} in canopy levels 2, 3, and 4 were approximately twice as long as those in canopy level 1, while the differences in CDT_{obs} between canopy level 2, 3, and 4 were not distinctive.

DISCUSSION AND CONCLUSIONS

Vertical variations in CDT_{obs} were estimated at this site using sap flow velocities (Figure 4). The length of CDT_{obs} in individual trees appears to be strongly related to meteorological conditions above and within the canopy, as well as to water storage holding on leaves in individual trees. Takanashi *et al.* (2003) reported that a coniferous forest stand (i.e. Japanese cypress forest) had stronger gradients of leaf drying time measured with wetness sensors between the upper and lower canopy than those of this study, despite the continuous canopy height of only 16 m with an LAI of 4.9 m² m⁻². In this coniferous forest, the gradients of leaf drying time between the upper and lower canopy spanned approximately 5 h. The gradients of leaf drying time between the upper and lower canopy in the present study were less than 5 h. This implies that wet leaves from the upper to the lower canopy dry out quickly after rainfall at this site, even though it has a 50 m height forest canopy.

The specific rainfall characteristics of this region could be the reasons for the less distinctive gradients of CDT_{obs} at this site, because spatial and temporal variations in rainfall are more significant in the tropics than in other climatic regions (Houze *et al.*, 1981; Shuin *et al.*, 1996); that is, cloudy weather after rainfall abruptly becomes sunny (Figure 4). For example, larger values of solar radiation (>800 W m⁻²), and vapour pressure

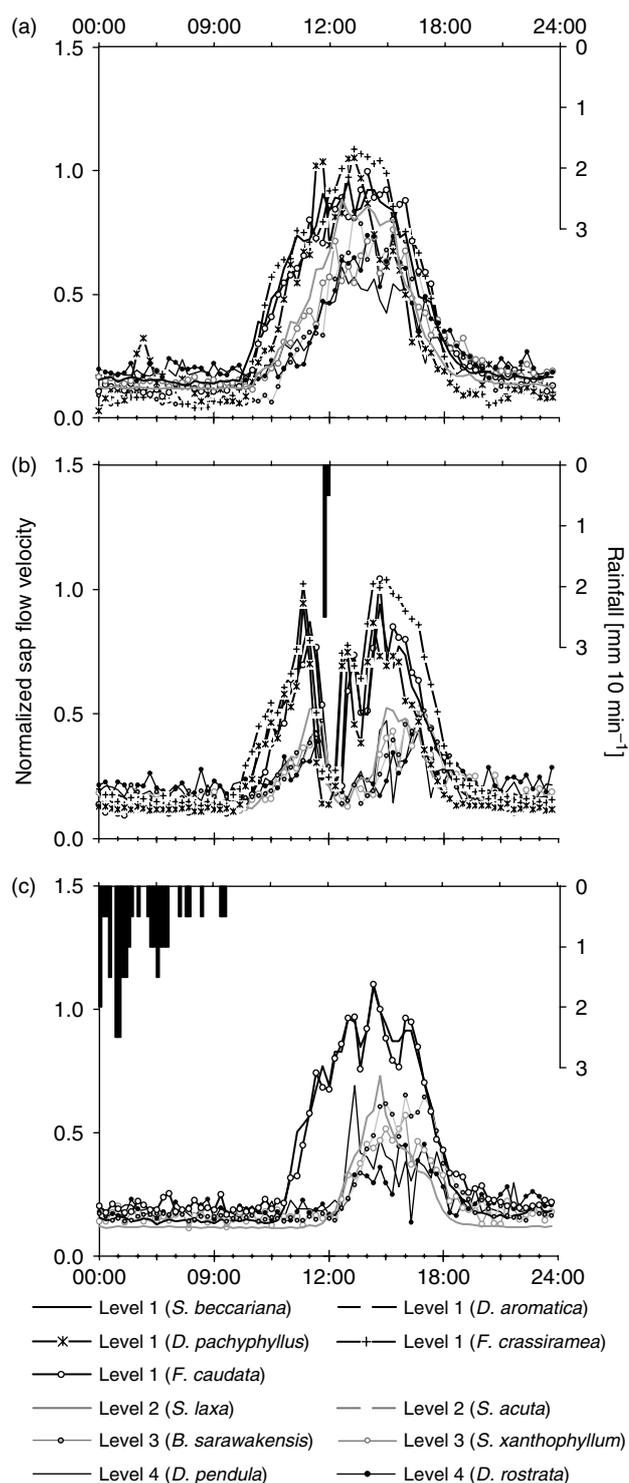


Figure 3. Typical diurnal variations in normalized sap flow velocities measured in individual trees in canopy levels 1, 2, 3, and 4 (Figure 1) with diurnal distributions of rainfall on (a) 28 August, (b) 24 August, and (c) 25 September. Sap flow velocities in individual trees were normalized by the maximum value in the measurement period for each tree

deficit (>5 hPa) were reached less than 2 h after daytime rainfall at this site (Figure 4), whereas solar radiation and vapour pressure deficit after morning rainfall in the coniferous forest stand remained lower than 400 W m⁻² and 5 hPa, respectively, during daytime. The significantly larger evaporative energy after rainfall at this site than

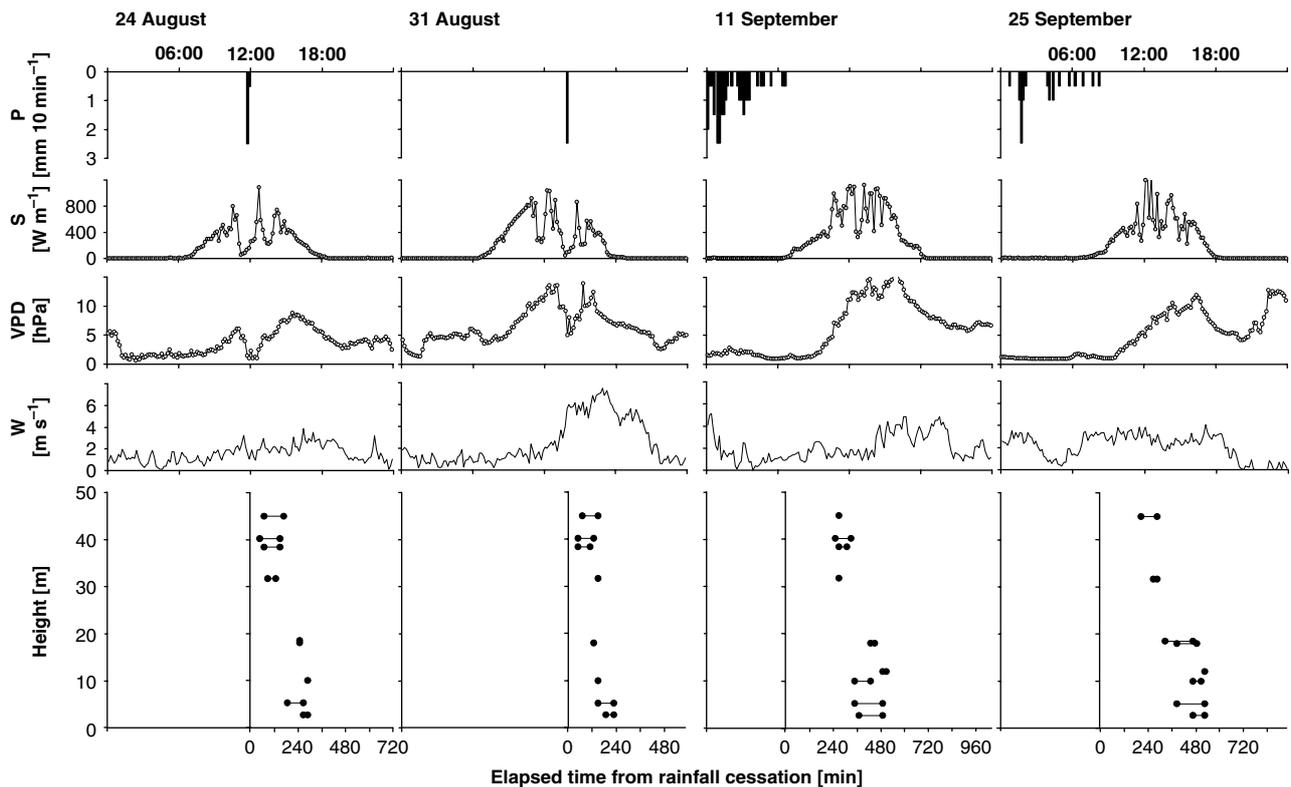


Figure 4. Vertical profiles of CDTobs on 24, 31 August, and 11, 25 September in 2004. Diurnal variations in rainfall (P), solar radiation (S), vapour pressure deficit (VPD), wind speed (W) measured above the canopy are also shown. Horizontal bars with circles at each end represent CDTobs in individual trees

at the coniferous forest stand may cause rapid drying of wet leaves within the forest canopy. Smaller canopy water storage capacity on leaves in tropical rainforests could be another reason for the less distinctive gradients of CDTobs. In a previous study, smaller canopy water storage capacity, *ca.* 0.7 mm, was reported at this site (Manfroi *et al.*, 2006; Kume *et al.*, 2007b) than that of Takanashi *et al.* (2003), which was *ca.* 1.0 mm (i.e. 0.2 mm LAI⁻¹) at the stand scale. Further, many previous studies have reported small canopy water storage capacity (<1.0 mm) in tropical forest at the forest canopy scale (Lloyd *et al.*, 1988; Jetten *et al.*, 1996; Dykes, 1997; Schellekens *et al.*, 2000).

This study reports the vertical variations in CDTobs in a Bornean tropical rainforest. Such vertical profiles have not previously been reported in tropical rainforests because of the large and complex canopy, and the lack of facilities for measuring canopy drying time within a forest canopy. The CDTobs profiles presented in this study are a useful illustration of a technique for studying wet-canopy evaporation in tropical rainforests, however, three major practical limitations should be considered. First, a possible time lag between canopy transpiration and stem sap flow may affect the availability of CDTobs. At this site time lags between canopy transpiration and stem sap flow are negligible, but the time lag should be considered at other sites before application of the method presented in this study using a time series analysis (Phillips *et al.*, 1999). Second, the utility of the proposed method is considerably limited by rainfall characteristics. Detecting

canopy wetness using sap flow measurements can work well in humid tropics where short rain events tend to occur in the morning and around midday. It would be difficult to apply this method in interior sites within the humid tropics where late afternoon or midnight rain events dominate in the diurnal cycle (Lloyd, 1990; Oki and Musiaka, 1994; Chappell *et al.*, 2001; Sorooshian *et al.*, 2002). This limitation may be overcome by using a sap flow velocity modelled on the basis of solar radiation and vapour pressure deficit (Komatsu *et al.*, 2006), instead of the sap flow velocity averaged over bright days. Third, physiological differences among tree species may influence the estimation of CDTobs. In fact, previous studies conducted in lowland dipterocarp rainforest showed variations among species in the diurnal courses of gas exchange due to specific stomatal responses to atmospheric conditions (Eschenbach *et al.*, 1998; Kenzo *et al.*, 2004). Further, stomatal control of transpiration in response to atmospheric conditions can differ under wet and dry soil conditions at this site (Kumagai *et al.*, 2004). Thus, to eliminate the effects of interspecific and temporal variations in physiological responses on estimation of CDTobs, the average diurnal variations in sap flow velocities on bright days should be calculated for each sample tree under wet soil conditions, as performed in this study.

Multi-layer models have not been applied previously to wet-canopy evaporation processes in tropical rainforests with complex canopy structures, thus, the applicability of multi-layer models for wet-canopy evaporation in a tropical rainforest is still unknown. Using the method for

profiles of CDTobs presented in this study in addition to conventional measurements (Watanabe and Mizutani, 1996; Manfroi *et al.*, 2006) can provide better validation of multi-layer models than when the conventional measurements alone are used. This is because CDTobs enables one to examine whether multi-layer models can reproduce wet-canopy evaporation processes within a forest canopy. Furthermore, sensitivity analysis using the validated multi-layer models will provide a better understanding of how forest canopy structure impacts on meteorological conditions and leaf drying time within a forest canopy.

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