Estimation of canopy drying time after rainfall using sap flow measurements in an emergent tree in a lowland mixed-dipterocarp forest in Sarawak, Malaysia

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Abstract:

This study emphasizes the importance of canopy drying time (CDT) after rainfall in a lowland tropical rain forest. In this study, we estimate CDT using sap flow velocities measured by a heat-pulse method in an emergent tree in a lowland mixed-dipterocarp forest. Estimated CDT (ECDT) for each rain event has been defined as the time from rainfall cessation to the specific time derived from the difference between diurnal courses of sap flow velocities on a rainy day versus bright days. ECDT could be derived for 22 rain events that were grouped into two types, depending on whether rainfall ceased before or after noon. The ECDTs were distributed more widely and with greater values when rainfall ceased before noon (Type 1) than after noon (Type 2). The ECDTs of both Type 1 and Type 2 decreased with increases in net radiation (R_n) and vapour pressure deficit (VPD) after rainfall. This result shows that ECDT is determined mainly by post-rainfall evaporation rates. The sap flow velocity as a detector of canopy wetness worked out well because of the specific rainfall characteristics at this site. The practical limitations of the method using sap flow velocities are discussed in relation to rainfall characteristics and time lags between transpirations and sap flow velocities. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS heat-pulse method; sap flow velocity; rainfall; canopy drying time (CDT); lowland mixed-dipterocarp forest

INTRODUCTION

An estimated 15% of forests in humid tropical Asia have been converted to other land uses within the last 15 years (Houghton and Hackler, 1999). Such regional land-use changes can lead to a decrease in evapotranspiration from the ground surface, a hydrological change that may occasionally reduce regional rainfall (Kanae *et al.*, 2001). To assess the effects of deforestation on a regional environment, it is important to understand water vapour-exchange processes between forest and atmosphere.

The water vapour-exchange processes, which consist mainly of wet canopy evaporation and dry canopy transpiration, are quite different depending on whether the canopy is wet or dry. Canopy drying time (CDT) is the period needed to dry out canopy exposed to rainfall; wet canopy gradually shifts to dry canopy. In a lowland tropical rain forest, short rain events occur more frequently than in other climatic regions (Kuraji, 1996), which leads to more frequent occurrences of CDT than in other climatic regions. In lowland tropical rain forests, understanding the variations of CDT will be one of the keys to estimating evapotranspiration over the long term.

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Received 18 November 2003

Accepted 9 February 2005

A numerical model for estimating evapotranspiration has been formulated using the different functions of wet and dry canopy (Rutter *et al.*, 1975; Watanabe and Mizutani, 1996; Bigelow, 2001; Bosveld and Bouten, 2003; Takanashi *et al.*, 2003; Tanaka *et al.*, 2003). To validate the models, transpirations or latent heat fluxes (Watanabe and Mizutani, 1996; Bosveld and Bouten, 2003; Takanashi *et al.*, 2003; Tanaka *et al.*, 2003), and measurements of throughfall and stem flow (Bigelow, 2001; Tanaka *et al.*, 2003) have been used. A recent study also uses CDT to validate the model (Takanashi *et al.*, 2003). Not including CDT as part of the data for validation may cause a serious error in estimating evapotranspiration, especially in lowland tropical rain forests, where short rain events occur frequently throughout the year. However, there is little understanding of CDT characteristics in lowland tropical rain forests.

When examining CDT, canopy wetness should be measured *in situ*. To this aim, several methods of monitoring plant wetness have been investigated, including a wetness sensor developed by plant pathologists (Wei *et al.*, 1995; Giesler *et al.*, 1996; Miranda *et al.*, 2000). Since the wetness sensor measures leaf-scale wetness (3 cm × 3 cm; Miranda *et al.*, 2000), a series of wetness sensors must be placed at different heights within a canopy, and then the method applied to the entire canopy. Remote-sensing techniques, such as those based on gamma-rays (Calder and Wright, 1986) and microwaves (Bouten *et al.*, 1996), allow continuous monitoring of the canopy through complex calibrations. Although they can measure canopy-scale wetness (a sensor and receiver were each installed on separate towers standing 15 m apart; Bouten *et al.*, 1996), they are expensive to implement, and some platforms are required to install the series of wetness sensors and remote sensors within a canopy. Lowland tropical rain forests are characterized by tall emergent trees, which are sometimes taller than 70 m in Southeast Asia (Kira, 1978). This makes it difficult to apply these techniques in the lowland tropical rain forests, and may be one of the reasons why knowledge of CDT characteristics is lacking for this type of ecology.

Rainfall reduces transpiration, because evaporative energy is consumed for evaporating the water on the canopy (Rutter *et al.*, 1975; Bosveld and Bouten, 2003). It is still possible to derive valuable information on canopy wetness when reduction of transpiration by rainfall occurs by measuring the sap flow velocity to estimate tree transpiration. This can be conducted easily and interfaced readily through data loggers for long-term observations (e.g. Swanson, 1994; Wullschlegel *et al.*, 1998).

In this study, we propose that CDT can be estimated using sap flow velocities measured by a heat-pulse method. We discuss the reasons for using this method and its practical limitations. Although this paper examines estimated CDT characteristics in an emergent tree in a lowland mixed-dipterocarp forest, we are not attempting to validate the results obtained using sap flow velocity by independent canopy wetness observations. Even so, we believe this paper has novelty, because, to our knowledge, there are no other studies dealing with a wet canopy drying process in lowland tropical rainforests using sap flow measurements.

METHODS

Site

The study site is located in Lambir Hills National Park, Sarawak, Malaysia (4°20'N, 113°50'E), situated about 30 km southwest of Miri, the capital of the Fourth Division, Sarawak, and about 12 km from the nearest coast (Figure 1). The mean annual temperature at Miri Airport, situated 24 km northeast of the park, is about 27°C with slight seasonal variation. The mean annual rainfall at the airport is about 2700 mm and is distributed evenly throughout the year.

The park has an area of 6949 ha, 85% of which is covered by the lowland mixed-dipterocarp forest common to Borneo (Yamakura *et al.*, 1995; Itoh *et al.*, 1997; Condit *et al.*, 2000), with a continuous canopy height of approximately 50 m. The park contains a 49.5 m tree tower. Kumagai *et al.* (2001) has reported the total leaf area index of the site (5.1 m² m⁻²) and its vertical profile using the tower. The target tree in this study was an emergent tree, *Dipterocarpus pachyphyllus*, adjacent to the tower (Figure 2) about 48 m in height with a diameter at 5 m from the ground of 136.1 cm (Hiromi *et al.*, 1999).

Figure 1. Study site, situated about 30 km southwest of Miri in Sarawak, Malaysia

Figure 2. Schematic representation of the tree tower, equipment, and the target tree

Sap flow determined by the heat-pulse method

Sap flow velocities were measured continuously from June 2001 through to March 2002 using the thermoelectric heat-pulse method (Closs, 1958; Marshall, 1958). The instrumentation consisted of three sets of a sensor (HP-1, Hayasi Denko Co., Tokyo, Japan) containing a heater probe and two thermistor probes (2.0 mm in diameter, 50 mm in length). The heater probe was inserted radially into the target tree branch about 35 m above ground level. Two thermistor probes were vertically aligned asymmetrically around the heater probe. The upper probe and lower probe were spaced 10 mm and 7 mm respectively from the heater probe. The three sensors were installed in holes drilled with a gauge guide into the outer xylem to a depth of 20 mm, as shown in Figure 2. A heat-pulse tracer was released for a duration of 1.5 s every 20 min, and the temperature difference between thermistor probes was measured every 0.25 s. The time delay for the same temperature increase to occur at both thermistor probes was recorded with a solid-state memory module (CR10X, Campbell Scientific Inc., Logan, UT, USA). Heat pulse velocities were calculated by Closs's (1958) method as follows:

$$\text{HPV} = \frac{\text{OA} - \text{OB}}{2t_0} \times 3600 \quad (1)$$

where HPV (cm h^{-1}) is the heat pulse velocity, OA (cm) is the distance from the heater probe to the upper probe, OB (cm) is the distance from the heater probe to the lower probe, and t_0 (s) is the time delay for the same temperature increase to occur at both thermistor probes. In this instrumentation, a minimum measurable HPV is 0.63 cm h^{-1} , as a maximum t_0 was set for 860 s. Kominami and Suzuki (1993) have validated the measurement accuracy of this type of system by comparing it with stem cutting methods.

To account for the influence of sap flow interruption around an implanted sensor, the HPV calculated by Equation (1) was adjusted to sap flow velocities using Swanson's method (Swanson and Whitfield, 1981; Kominami and Suzuki, 1993). Yoshifuji *et al.* (2001) reported that HPV values decreased gradually in long-term, continuous measurements. To eliminate the influence of the gradual decrease caused by long-term observation, some adjustments should be made in addition to Swanson's method.

Previous studies have indicated that tree sap flow tends to plateau under conditions of high solar radiation and vapour pressure deficit (VPD; Hogg and Hurdle, 1997; Meinzer *et al.*, 1993; Granier *et al.*, 1996), which suggests that sap flow velocities will be nearly the same under conditions of high solar radiation and VPD. Therefore, adjustments for the decreasing of long-term sap flow velocities can be made as follows. (1) A linear regression equation can be derived between the date and the observed daily sap flow velocities on bright days. From this equation, the daily sap flow velocity expected on a bright day can be calculated for all day. (2) All observed daily sap flow velocities can be adjusted using the ratio of the daily sap flow velocity expected on a bright day to the intercept of that equation. This intercept would be the sap flow velocity expected on a bright day without the influence of a gradual decline. (3) The adjusted daily sap flow velocities are then adjusted for each time in proportion to what was observed every 20 min each day.

Definition of estimated CDT

Transpiration is reduced during the period of canopy wetting, because evaporative energy is consumed for evaporating the water on the leaves. When evapotranspiration from wet canopy is calculated using a numerical model, it is assumed that the proportion S/S_{max} (i.e. the ratio of the actual water stored on the leaves to the canopy saturation value) of the total leaf area is covered by intercepted water, whereas the rest of the area is open to transpiration (e.g. Rutter *et al.*, 1975; Watanabe and Mizutani, 1996; Bosveld and Bouten, 2003). In addition, physiological responses for rain are also reported. The stomata of leaves close momentarily when exposed to rain (Monzi, 1937; Ishibashi and Terashima, 1995), and the water droplets block the leaves' stomata obstructing gas exchange (Kimura and Tanakamaru, 1982).

A canopy dries gradually after rainfall, starting from the top (Watanabe and Mizutani, 1996; Takanashi *et al.*, 2003). As transpiration starts on the dry portion of the leaves, sap flow can be measured before the lower part of the canopy has dried. Takanashi *et al.* (2003) measured the sap flow velocities in the basal stem

while measuring the leaf wetness using wetness sensors placed at different heights within the canopy. They showed that sap flow velocity after rainfall peaked at around the time when the lower canopy had completely dried in the afternoon. This suggests that sap flow velocity can be used as an integrator of leaf wetness throughout the canopy of an entire tree.

Generally, factors determining sap flow are solar radiation and VPD (Meinzer *et al.*, 1993; Becker, 1996; Granier *et al.*, 1996; Hogg and Hurdle, 1997; Cienciala *et al.*, 2000; O'Brien *et al.*, 2004), temperature (Lopushinsky, 1986), soil moisture (Kuwada *et al.*, 2002; Lagergren and Lindroth, 2002; Martinez-Vilalta *et al.*, 2003), and canopy wetness. Around this study area, seasonal variations of temperature and solar elevation are small, and the rainfall is distributed evenly throughout the year. This means that sap flow velocity measured at the same time on bright days can have almost the same value throughout the year. When sap flow velocity after rainfall is lower than sap flow velocity expected on a bright day, the decrease is caused by low solar radiation due to cloud cover, low VPD and canopy wetness. Thus, it might be possible to derive an indication of canopy wetness by comparing the measured sap flow velocity and the sap flow velocity modelled on the basis of solar radiation and VPD. However, the model of sap flow velocities is just being developed (O'Brien *et al.*, 2004), and is too complex for our purpose. Instead of the modelled sap flow, we use the sap flow velocity averaged over 20 bright days. When sap flow velocity after rainfall equals the value of the average sap flow velocity over 20 bright days, we consider that the effect of leaf wetness on transpiration is removed and that the canopy is completely dry.

Figure 3 shows the diurnal courses of the sap flow velocity averaged over 20 bright days with standard deviation and the sap flow velocity for a rainy day, as well as during the actual rainfall. In this study, estimated CDT (ECDT) has been defined as follows:

$$ECDT_S \leq ECDT \leq ECDT_L$$

Figure 3. Definition of estimated canopy drying time (ECDT): (a) rainfall P ; (b) diurnal courses of sap flow velocity during a rainy day (black line) and the average over 20 bright days (grey line). Vertical bars indicate the standard deviation. $ECDT_S$, $ECDT_L$, A , S , L are defined in the text

where $ECDT_S$ is defined as the period from A to S and $ECDT_L$ is defined as the period from A to L ; A is the time when rain ceased, S is the time when sap flow velocity after rainfall exceeded the average minus the standard deviation of the sap flow velocity averaged over 20 bright days, and L is the time when sap flow velocity after rainfall exceeded the average sap flow velocity over 20 bright days. In this study, we suppose that the wet canopy dries out completely during the period from S to L , and so $ECDT$ has been defined as ranging between $ECDT_S$ and $ECDT_L$ at each rain event. If sap flow velocity after a rainfall exceeds the average and the average minus the standard deviation of the sap flow velocity over 20 bright days at one interval, then time S will be equal to time L and $ECDT_S$ will be equal to $ECDT_L$.

For example, the total rainfall measured for 401 min from 04:12 to 10:53 amounted to 16.5 mm on 16 June (Figure 3). Sap flow velocities were quite low until around noon. Subsequently, the sap flow velocity increased abruptly and exceeded the average minus the standard deviation of the sap flow velocity over 20 bright days at 13:00 (time S). After 40 min, sap flow velocity exceeded the average sap flow velocity at 13:40 (time L). In this case, $ECDT_S$ and $ECDT_L$ are defined as 127 min and 167 min respectively, and $ECDT$ is defined as the range between 127 and 167 min. In this analysis, only the sap flow velocities measured with one of the three sensors were used, since the diurnal courses of measurements from each sensor exhibited a remarkable concordance.

Meteorological measurements

Equipment was installed at the top of the 49.5 m tower (Figure 2). Air temperature and relative humidity, measured using a thermohygrograph (HMP45A, Vaisala Co., Helsinki, Finland), were recorded with a data logger (SQ1250, Grant Instruments, Cambridge, UK). Net radiation (R_n) was calculated using downward and upward shortwave radiation and downward and upward longwave radiation measured using solarimeters (MS402, Eko Instruments Co., Tokyo, Japan) and infrared radiometers (MS202F, Eko Instruments Co., Tokyo, Japan) respectively. Data acquisitions were made using solid-state memory modules (CR10X, Campbell Scientific Inc.). Rainfall was measured using a tipping-bucket rain gauge (20 cm in diameter and 0.5 mm in tip resolution; Ohta Keiki Co., Tokyo, Japan) and a data logger (Kadec-PLS, Kona System Co., Sapporo, Japan).

RESULTS AND DISCUSSION

The following three criteria were used to select target rain events: (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. The reasons for the three criteria are that sap flow velocity varies markedly in the daytime, and we wanted to deal with rain events that left the canopy fully wet at the time rainfall ceased.

Research on tropical rain forests has measured canopy water storage capacities of less than about 1.5 mm (e.g. Lloyd *et al.*, 1988; Jetten, 1996; Dykes, 1997; Schellekens *et al.*, 2000). Thus, a threshold of 1.5 mm is enough rainwater to wet the canopy fully. To guarantee a completely wet canopy at the time rainfall ceased there is the question of whether or not the canopy is drying during a short no-rain period in a rain event. In our study, we included no-rain periods of 2 h or less, which is shorter than the no-rain periods in previous reports on tropical rain forests. Most of the periods in previous reports are in the 3–12 h range (e.g. Jackson, 1975; Lloyd *et al.*, 1988; Asdak *et al.*, 1998; Schellekens *et al.*, 2000; Manfroi *et al.*, 2004). Additionally, we made sure that sap flow velocity remained low during our target rain events. This suggests that almost the entire leaf surfaces are wetted during rain events. Therefore, it is likely that any drying during the short no-rain periods rarely affects the wet canopy conditions at the time rain ceases in this study.

Table I shows the rainfall characteristics for 22 rain events satisfying our three criteria. Rainfall duration ranged from 1 to 541 min. Mean intensity ranged from 1.2 to 68.2 mm h⁻¹. Instantaneous maximum intensity,

Table I. Characteristics of the rain events

Date	Rain event					
	Starting time	Cessationtime	Duration (min)	Mean intensity (mm h ⁻¹)	Instantaneous ^a maximum intensity (mm h ⁻¹)	Total (mm)
21 Jun 2001	04:14	06:06	112	5.9	64.3	11.0
27 Jun 2001	12:42	12:50	8	49.5	78.3	6.0
30 Jun-2001	04:32	07:35	183	5.1	81.8	15.5
16 Jul 2001	04:12	10:53	401	2.5	20.7	16.5
22 Jul 2001	03:19	06:00	161	6.5	26.5	17.5
26 Jul 2001	00:45	07:15	390	2.8	30.5	18.5
28 Jul 2001	12:15	12:30	15	8.3	12.2	2.0
2 Aug 2001	12:52	12:53	1	58.1	46.2	1.5
3–4 Aug 2001	23:29	08:30	541	3.6	54.5	32.5
30 Aug 2001	15:07	15:41	34	10.3	41.9	6.0
9 Sep 2001	03:23	09:29	366	2.3	42.9	14.0
17 Sep 2001	12:52	13:55	63	68.2	300.0	71.0
3 Oct 2001	08:28	09:43	75	1.2	1.1	1.5
9 Jan 2002	13:52	13:57	5	18.2	12.8	1.5
17 Jan 2002	07:03	10:17	194	4.5	66.7	14.5
13 Feb 2002	14:59	15:05	6	46.8	81.8	5.0
15 Feb 2002	06:14	07:27	73	3.3	56.3	4.0
20 Feb 2002	04:31	07:03	152	1.2	1.9	3.0
22 Feb 2002	05:14	07:54	160	1.5	10.1	4.0
24 Feb 2002	13:41	14:49	68	11.0	81.8	12.5
26 Feb 2002	12:07	14:11	124	7.0	90.0	14.5
27 Feb 2002	12:53	13:01	8	10.5	11.4	1.5

^a These values were calculated using the minimum time interval it takes to refill the 0.5 mm tipping bucket for each rainfall event.

which was calculated using the minimum time to refill the 0.5 mm tipping bucket at each rain event, ranged from 1.1 to 225.0 mm h⁻¹. Total rainfall at each rain event was within 71.0 mm.

Figure 4 shows the relationship between the time that rainfall ceases and ECDT. When rainfall ceased before noon, ECDTs were distributed widely: the midpoint between ECDT_S and ECDT_L at each event ranged from 126 to 534 min, with a mean midpoint of 240 ± 116 ($n = 12$). The slanted, broken line in Figure 4 indicates the time remaining until noon at each rainfall cessation. A number of ECDTs are plotted around this line, indicating that sap flow velocities remained low until around noon if the rainfall event ceased before noon. However, ECDTs were distributed more narrowly when rainfall ceased after noon: the midpoint between ECDT_S and ECDT_L at each event ranged from 39 to 183 min, with a mean midpoint of 93 ± 41 min ($n = 10$). The distributions of ECDT were quite different before and after noon. In this paper we grouped rain events into two types: Type 1 represents rain events that ceased before noon and Type 2 represents rain events that ceased after noon.

Factors determining ECDT

Figure 5 shows typical diurnal courses of sap flow velocity for Type 1 and Type 2 rainfall events, as well as Rn and VPD with the average diurnal course for bright days. Total rainfall was recorded as 32.5 mm during the 541 min between 23:29 on 3 August and 08:30 on 4 August 2001 (Type 1). After the rainfall, Rn and VPD increased slowly compared with the average diurnal course for bright days. During the same period, the sap flow velocity increased as slowly as Rn and VPD, and the ECDT was $200 \leq \text{ECDT} \leq 360$ min. On 17 September (Type 2), total rainfall was 71 mm during the 63 min between 12:52 and 13:55. Sap flow velocity increased as rapidly as Rn and VPD after the rainfall. In this case, the ECDT was $65 \leq \text{ECDT} \leq 145$ min.

Figure 4. ECDT in relation to the time rainfall ceased. ECDT for each rain event is indicated as the range between ECDT_S and ECDT_L for each rain event. The slanting broken line indicates the time remaining until noon after each cessation time

CDT generally varies according to evaporation rates after rainfall under the condition that the canopy is fully wet, since evaporation rate is the important factor controlling wet canopy evaporation (e.g. Rutter *et al.*, 1975; Gash, 1979; Suzuki *et al.*, 1979).

Evaporation rates increase with increasing R_n and VPD according to the Penman (1948) equation. To examine the relationships between ECDT, R_n , and VPD, the following terms are defined: $\overline{R_n}$ is the mean R_n in the period from A to the midpoint between S and L ; $\overline{VPD}$ is the mean VPD in the period from A to the midpoint between S and L . Figure 6 shows the relationships between ECDT, $\overline{R_n}$ and $\overline{VPD}$, as well as the relationship between $\overline{R_n}$ and $\overline{VPD}$. Although ECDT mainly decreases with increasing $\overline{R_n}$, Type 2 events had shorter ECDTs than Type 1 events, and the relationship between ECDT and $\overline{R_n}$ was clearer for the Type 2 rainfall events than the Type 1 events (Figure 6a). We found a positive linear relationship between $\overline{R_n}$ and $\overline{VPD}$ for both rainfall types (Figure 6c), but several Type 2 events with $\overline{R_n} < 250 \text{ W m}^{-2}$ had $\overline{VPD}$ values greater than those of Type 1 events, which may cause the ECDTs after Type 2 rainfall events with $\overline{R_n} < 250 \text{ W m}^{-2}$ to be shorter than those of Type 1 (Figure 6a). ECDT also decreases with increasing $\overline{VPD}$ (Figure 6b). We found the same tendency in the relationships between ECDT_S and the mean R_n and the mean VPD in the period from A to S , and the relationships between ECDT_L and the mean R_n and the mean VPD in the period from A to L .

ECDTs of both Type 1 and Type 2 events decreased with increasing R_n and VPD. These results suggest that ECDT is determined mainly by the evaporation rate after rainfall. This relationship between ECDT and the evaporation rate corresponds with the general relationship suggested by previous studies (Rutter *et al.*, 1975; Gash, 1979; Suzuki *et al.*, 1979) and suggests that ECDT can be used as part of the data validating a wet canopy evaporation model.

Practical limitations of sap flow measurements for detecting canopy wetness

Using sap flow measurements for detecting canopy wetness has an advantage over the use of wetness sensors placed at different heights within a canopy, because sap flow velocities that can be measured readily at a single sensor provide information about integrated leaf wetness conditions throughout the canopy of an

Figure 5. Typical diurnal courses for Type 1 and Type 2: (a) rainfall P ; (b) sap flow velocity; (c) R_n ; (d) VPD . Values averaged over 20 bright days are also shown with the standard deviations indicated by vertical bars. $ECDT_S$, $ECDT_L$, A , S , L are defined in the text

Figure 6. $ECDT$ in relation to (a) $\overline{R_n}$, (b) $\overline{VPD}$, and (c) the relationship between $\overline{R_n}$ and $\overline{VPD}$ for Type 1 (○) and Type 2 (■). The line in (c) was drawn by hand to show the tendency of the relationship; it is not a regression line

entire tree. However, there are two major practical limitations to be considered: one is an issue concerning rainfall characteristics, the other is the time lag between transpiration and sap flow through a stem.

Successfully detecting canopy wetness using sap flow measurements depends on the rainfall characteristics of the forest under study. In our study, total rainfall in the data set period was distributed over 94 rain events,

Figure 7. Total rainfall at each rain event in relation to the time of rainfall cessation in 94 rain events. The 94 rain events were the rain events that were separated by a no-rain period of 2 h. The Y-axis is represented by a logarithmic scale. The closed grey circle indicates a target rain event; the open diamond indicates a rain event that was not selected as a target rain event in this study

when the rain events were separated by no rain periods of 2 h. Figure 7 shows the relationship between the time that rainfall ceased and the total rainfall in 94 rain events. Forty-three rain events (46% of 94 rain events) ceased during the night from 17:00 to 06:00; these rain events were omitted. There were 23 rain events (24% of 94 rain events) among 51 rain events in which rainfall ceased in the daytime from 6:00 to 17:00 but did not exceed the threshold of 1.5 mm. Thus, these 23 rain events were omitted. Among 28 rain events in which the total rainfall exceeded the threshold of 1.5 mm, we could not calculate ECDT for six of them (7% of 94 rain events), as the sap flow velocities after rainfall remained low until sunset. Consequently, the residual 22 rain events (23% of 94 rain events) were selected as target rain events. The specific rainfall characteristics at this site made it possible to record a sufficient number of rain events.

Figure 8 shows the diurnal cycle and seasonal changes in rainfall (adapted from Kuraji *et al.* (2001)). Rainfall at this site has a distinct diurnal cycle, with two peaks: one in the middle of the night from 23:00 to 02:00 and the other in the afternoon from 13:00 to 15:00 (Figure 8a). Most rainfall events can be divided into two types: midnight rainfall around the midnight peak and afternoon rainfall around the afternoon peak. It seems that midnight rainfall tends to cease in the morning at the latest and rarely occurs during the period between 08:00 and 12:00 (Figure 8c). In the afternoon, the rainfall rarely occurs between 15:00 and 18:00 (Figure 8c). In this study, regularly occurring periods of no rain in a 24 h day were helpful for estimating CDT using sap flow velocities. We can surmise that detecting canopy wetness by measuring sap flow velocity will also work well in the Amazonian forest (e.g. Lloyd, 1988) and the Malay Peninsula (Noguchi *et al.*, 2003), where short rain events tend to occur in the daytime. On the other hand, it would be difficult to use this technique in eastern Puerto Rico (Schellekens *et al.*, 2000), where rainfall occurrence is higher at night-time than during daylight hours.

This method may also be limited by a possible time lag between transpiration and sap flow that may affect the availability of ECDT in some cases. It has been reported that the change of sap flow in a basal stem trailed canopy transpiration (e.g. Phillips *et al.*, 1997, 1999; Goldstein *et al.*, 1998). This time lag was found

Figure 8. Rainfall at each time of day for each month. Data were adapted from Kuraji *et al.* (2001): (a) diurnal cycle of rainfall; (b) seasonal change of rainfall; (c) diurnal cycle of rainfall in each month

to be caused by internal water storage and hydraulic resistance in a tree (Landsberg *et al.*, 1976; Kumagai, 2001).

However, at this site, a remarkable time lag between crown and basal sap flow was not observed when sap flow velocities in a branch at 50 m above the ground and at the stem above the buttresses were measured in another dipterocarp emergent tree (T. Kume, personal communication). This suggests that very similar results would be obtained regardless of sensor positions, and that the sensor could be installed at a more accessible point. On the contrary, when time lags were evidently observed (e.g. Phillips *et al.*, 1997, 1999; Goldstein *et al.*, 1998), the time lag would have added to the ECDT. Furthermore, it has been reported that the time lag became obvious only in the night and that the nocturnal sap flow occurred to refill internal water storage in a tree (e.g. Kenworthy, 1969; Caspari *et al.*, 1993). This also makes it difficult to estimate CDT using sap flow velocities. However, such a nocturnal sap flow became obvious under severely dry conditions (Caspari *et al.*, 1993). Thus, nocturnal sap flow rate might be low after a rainfall, to the extent that sap flow cannot be measured correctly by the heat-pulse method, and a limitation of this method is insensitivity at low sap flow rates (Becker, 1998).

This study reports the distributions and the determining factors of ECDT in the upper canopy using measurements in a single branch in a lowland tropical forest. When the time lag is negligible or corrected,

the canopy drying process within a forest canopy in a tropical rain forest will also be examined using sap flow velocities measured at an accessible level without a special platform.

CONCLUSIONS

CDT after rainfall is one of the key aspects to understanding evapotranspiration processes in a lowland tropical rain forest, because of this forest's specific rainfall characteristics. In this study, ECDT has been defined as a range from ECDT_S (the shorter estimation) to ECDT_L (the longer estimation). ECDT_S and ECDT_L have been defined as two periods each beginning at the time rainfall ceased and each ending at a specific time derived from the difference between typical diurnal courses of sap flow velocities on bright days versus the measured sap flow on a rainy day. This study indicated the ECDT for each rain event and examined the factors determining ECDT in an emergent tree in a lowland mixed-dipterocarp forest.

ECDT could be derived for 22 rain events out of 94 rain events recorded at the study site that could be distinctly divided into two types. When rainfall ended before noon (Type 1), ECDTs were distributed more widely and with greater values than when rainfall ceased after noon (Type 2). The ECDTs of both Type 1 and Type 2 events decreased with increasing R_n and VPD after rainfall. These results show that ECDT is determined mainly by evaporation rates after rainfall, suggesting that ECDT can be used as part of the data for validating a wet canopy evaporation model.

Rainfall at this site has two distinct peaks in the diurnal variation pattern, one near midnight and the other in the afternoon, with periods when rainfall rarely occurs being observed in the morning and the afternoon. This diurnal variation pattern makes the estimation of CDT using sap flow velocities work well. When time lags between transpirations and sap flow in a basal stem can be considered, more measurements on individual trees encompassing various heights will allow a better understanding of canopy drying processes within a forest canopy.

ACKNOWLEDGEMENTS

This work was supported by the CREST program of the JST (Japan Science and Technology Corporation). We would like to express our appreciation to the Forest Research Center of the Sarawak Forestry Corporation and the Forestry Department Sarawak, for their cooperation with our work in Lambir. Some of the meteorological equipment was installed by Dr Tomo'omi Kumagai of the University of Kyushu, Dr Katsunori Tanaka of the Frontier Research System for Global Change, and Ms Yuri Tanaka. Fruitful discussions with Dr Nobuaki Tanaka, Dr Hikaru Komatsu, Mr Norifumi Hotta and Mr Odair José Manfroí, from the University of Tokyo, and two anonymous reviewers' comments are also greatly appreciated.

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