Water Resources Systems—Water Availability and Global Change (Proceedings of symposium HS02a held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 280, 2003.

Long-term estimation of evapotranspiration from a tropical rain forest in Peninsular Malaysia

MAKOTO TANI[1], ABDUL RAHIM NIK[2], YUKIO YASUDA[3],
SHOJI NOGUCHI[4], SITI AISAH SHAMSUDDIN[2],
MOHD MD SAHAT[2] & SATORU TAKANASHI[1]

1 *Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*
tani@kais.kyoto-u.ac.jp

2 *Forest Research Institute Malaysia, Kepong, 52109 Kuala Lumpur, Malaysia*

3 *Forestry and Forest Products Research Institute, Matsunosato 1, Tsukuba, Ibaraki 305-8687, Japan*

4 *Japan International Research Center for Agricultural Sciences, 1-1,Ohwashi, Tsukuba, Ibaraki 305-8686, Japan*

Abstract Field observations for estimating long-term evapotranspiration from a tropical rain forest were made in the Pasoh Forest Reserve, Peninsular Malaysia. The Penman-Monteith-Rutter model was applied to four-years of meteorological records to enable continuous estimation of evapotranspiration during dry and wet canopy conditions. The estimates show that the annual average total evapotranspiration, transpiration and interception loss for 1996–1999 were 1548 mm, 1218 mm and 331 mm, respectively, cf. annual rainfall of 1571 mm and net radiation of 1744 mm (water equivalent). Although a long dry period was included as a result of the strong El Niño in 1997 and 1998, evapotranspiration always accounted for a large portion of the net radiation.

Key words El Niño; evapotranspiration; Pasoh Forest Reserve, Malaysia; Penman-Monteith-Rutter model; tropical forest

INTRODUCTION

Long-term estimation of evapotranspiration from tropical rain forest is important from aspects of both hydrological and climatic issues. In Southeast Asia, some estimation results, based on annual water budgets in small study catchments, have been documented (Bruijnzeel, 1990). However, such results give us only annual evapotranspiration amounts and very little information relating to long-term characteristics, including the responses to environmental variables. In the Pasoh Forest Reserve, meteorological observations above the tropical rain forest were made using a 52-m tower, and evapotranspiration estimated through the Bowen ratio method (Tani *et al.*, 2003). This study showed that most radiant energy was used for latent heat of evapotranspiration, even in dry seasons, and that the surface conductance was controlled by the same functions of solar radiation and specific humidity deficit in both dry and rainy seasons. Attempts to estimate long-term continuous evapotranspiration throughout dry and wet canopy conditions using results from short-term flux measurements by an eddy covariance method, and from throughfall and stemflow measurements, are reported here.

STUDY SITE AND OBSERVATION DESIGN

This study was conducted in the Pasoh Forest Reserve of FRIM in Negeri Sembilan in Peninsular Malaysia (2°58′N, 102°18′E). The climate is characterized by small seasonal variations, and the southwest and northeast monsoons yield only small rainfall peaks around April and November. The annual rainfall of the normal year observed from 1983 to 1999 at a meteorological station (Pasoh Dua) near our site was 1804 mm. The core area (650 ha) of the Pasoh Forest Reserve (2450 ha) is covered with a primary lowland mixed Dipterocarp forest, which consists of various species of *Shorea* and *Dipterocarpus*. The continuous canopy height is about 35 m, although some emergent trees exceed 45 m. The leaf area index (LAI) was 6.52.

Meteorological variables were monitored by sensors installed at 52.6 m height on a tower. Continuous records were obtained for downward and upward solar radiation, net radiation, air temperature, humidity, wind direction, wind velocity, and rainfall. Air temperature and vapour pressure for the estimation of evapotranspiration by the Bowen ratio method were measured by two ventilated psychrometers at 43.6 and 52.6 m. One-week of observations of a closed-path eddy covariance system was conducted in March 1998 (Yasuda *et al.*, 2003). Friction velocity, sensible heat, latent heat and CO_2 flux were estimated from these observations. Throughfall and stemflow were monitored near the tower. The throughfall was measured by 20 pots, each with an area of 366.4 cm^2, in a square plot of 20 × 15 m, and stemflow was measured from seven trees reaching the upper canopy layer in a square plot of 10 × 15 m within the throughfall plot. Interception loss was calculated from the difference between gross rainfall above the canopy at the height of 52.6 m and the total of throughfall and stemflow.

A model system composed of a big-leaf parameterization and interception model is necessary for estimating long-term evapotranspiration from dry and wet canopies. The Penman-Monteith equation for the big-leaf parameterization and the Rutter model for the interception component has been widely used for the estimation (Shuttleworth, 1988). Hence, the Penman-Monteith-Rutter model was also employed for our estimation. For the application of this model, potential evaporation from the wet canopy is first calculated from the aerodynamic resistance, and the actual evaporation can be calculated from the potential value and current water storage on the canopy, where the saturation storage capacity maximum can be estimated from the throughfall and stemflow measurements. Calculating actual evapotranspiration from the dry canopy needs an additional parameter, that is, surface resistance representing the control by stomata. Characteristics of the surface resistance, the reciprocal of surface conductance, had already been analysed and its functional relationship to solar radiation and specific humidity deficit was fixed from the analysis (Tani *et al.*, 2003). The evaluation of aerodynamic resistance and canopy storage capacity are discussed later in this paper.

MODEL DESCRIPTION

Long-term evapotranspiration was estimated using the Penman-Monteith-Rutter model, following its application to Amazonian rain forest by Shuttleworth (1988). Actual evapotranspiration is composed of evaporation from the wet canopy and evapotranspiration from the dry canopy and is calculated as their total when some portion of the canopy is wet and other parts are dry, during and after a rainfall event. The potential evapotranspiration values from the totally wet and dry canopies (E_c and E_t) can be estimated by the Penman-Monteith equation as:

$$lE = (\Delta Q + \rho c_p V_d / r_A) / \left[\Delta + c_p (1 + r_c / r_A) / l\right] \tag{1}$$

where E is the evapotranspiration, l is the latent heat of vaporization, Δ is the mean rate of change of specific humidity with temperature, Q is the available energy, V_d is the specific humidity deficit, ρ is the density of air, c_p is the specific heat at constant pressure, r_A is the aerodynamic resistance, and r_c is the surface conductance. E_c and E_t can be calculated if the values $r_c = 0$ and $r_c > 0$, respectively, are assumed.

The canopy storage characteristics have to be described by the Rutter model as:

$$\mathrm{d}C / \mathrm{d}t = P(1 - p - p_t) - (C / S) E_c - D \tag{2}$$

$$D = D_0 \exp[b(C - S)] \tag{3}$$

where C is the actual stored water on the canopy, S is the saturation storage capacity, P is the gross rainfall, p is the rainfall fraction falling directly to the ground, p_t is the rainfall fraction diverted to the trunks, E_c is the evaporation from the completely wet canopy, D is the drainage from the canopy, D_0 is the drainage rate when the storage on the canopy is equal to S, and b is an empirical parameter. Hence, the equation for estimating actual evapotranspiration (E_a) is written:

$$E_a = (C / S) E_c + (1 - C / S) E_t \tag{4}$$

RESULTS AND DISCUSSION

Annual amounts of throughfall, stemflow and interception

The relationships of throughfall, stemflow and interception to gross rainfall in each measuring period of about two weeks are plotted in Fig. 1(a)–(c), and show good linear correlations. The annual amounts of gross rainfall, throughfall, stemflow and interception from 1 July 1999 to 30 June 2000 were 2262.3, 1879.4, 6.8 and 381.3 mm, respectively. The ratios of the throughfall, stemflow and interception to gross rainfall were 83.1%, 0.3% and 16.9%. Another interception observation carried out in Pasoh Forest (Manokaran, 1979) showed the respective ratios to be 77.56%, 0.64% and 21.80%. The very small percentages of stemflow were remarkable in both studies as they were smaller than the values obtained from other tropical rain forests (e.g. Lloyd *et al.*, 1988; Jetten, 1996), that are usually even smaller than those obtained from temperate forests. Although our results on stemflow are not without doubt, due to forest heterogeneities, the contribution of its small absolute value to interception may be evaluated as insignificant in the overall evaporation estimation. The interception ratio of 16.9% in our estimate lies between 8.9% in the Amazon (Lloyd *et al.*, 1988) and 21% in West Java (Calder *et al.*, 1986).

Penman-Monteith-Rutter model application

Application of the Penman-Monteith-Rutter model first requires a parameter estimation process. However, estimating parameters in the Rutter model from relationships between gross rainfall, throughfall and stemflow was not easy mainly because the relationships are widely scattered (Fig. 1(a)–(c)). One strategy for optimizing

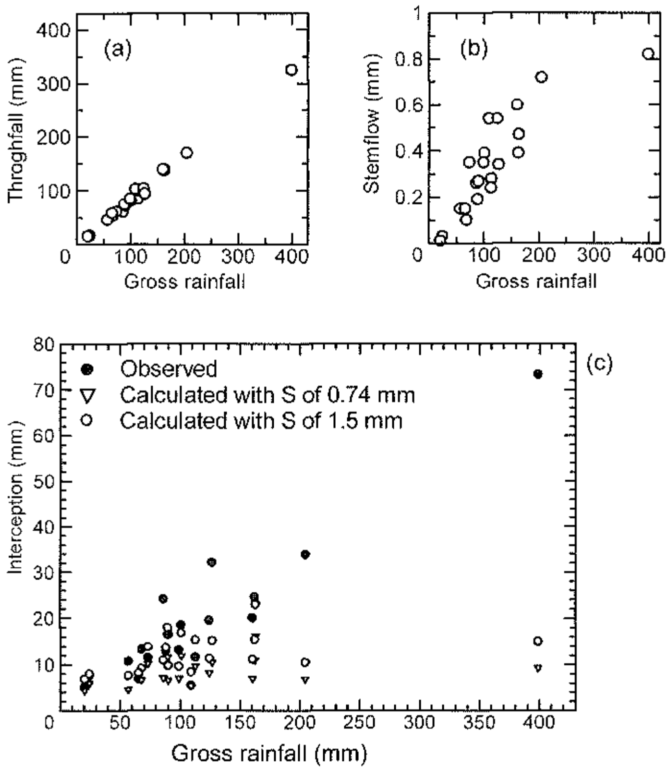

Fig. 1 (a) Relationships of throughfall to gross rainfall. (b) Relationships of stemflow to gross rainfall. (c) Relationships of interception to gross rainfall.

the parameter values is to first follow previous studies and to modify the values by comparisons between the tentative calculation results and the observations. A parameter value set was obtained for the Amazonian forest (Lloyd *et al.*, 1988). Thus, the assumed parameters were as $S = 0.74$ mm, $p = 0.08$, $D_0 = 0.0014$ mm min^{-1}, and $b = 5.25$. As the stem flow fraction was very small (Fig. 1(c)), p_t was assumed to be 0.

The Penman-Monteith equation requires values of aerodynamic resistance for the sensible and latent heat fluxes. We assumed that they are equal to the aerodynamic resistance for momentum, as used by similar estimations (e.g. Shuttleworth, 1988). Because the friction velocity was directly measured by the eddy covariance method, we calculated r_M from the relationship of $r_M = U/U^{*2}$, where U is the wind velocity and U^* is the friction velocity. In our estimates using this method, we derived simple relations between r_M and U for a long-term estimation because the observation by the eddy covariance method was carried out only for a week. Hence, we employ $r_A = 36.7/U$ for the daytime and $r_A = 123/U$ for the night-time.

Another parameter in the Penman-Monteith equation for calculating evapotranspiration from a dry canopy is a surface resistance or its reciprocal, surface conductance (g_c). Our previous study (Tani *et al.*, 2003) demonstrated that the following Jarvis type functional relationship of g_c (= $1/r_c$) was applicable to dry and wet conditions including the driest condition in 1998 due to the El Niño event:

$$g_c = 35[1.6S_d/(S_d + 0.6)]\exp(-80V_d) \qquad (5)$$

where S_d is the solar radiation. This relationship was used for our estimates.

Since parameter values in the Rutter model are tentatively given as similar values to those for Amazonian forest, the calculated results on interception were compared with the observations (Fig. 1(c)). The calculated values are much smaller than those observed, and the annual total of calculated interception was 182 mm compared with the observation of 381 mm, suggesting the saturation storage capacity (*S*) was too small. The LAI of 6.52 for Pasoh is slightly larger than that of 6.0 for Amazon, and this may be underestimated because another investigation in the Pasoh Forest Reserve determined a value of 7.99 (Kato, 1978). Therefore, we tried to use the maximum value based on a review on *S* of tropical forests (Jetten, 1996). As a result, the annual interception was calculated as 265 mm using a larger *S* value of 1.5 mm, but it is still smaller than the observation. A detailed comparison between the calculated and observed plots in Fig. 1(c) shows they are similar to each other within the range of small rainfall events. This may suggest that the parameters for storage capacity roughly represented the canopy storage capacity of Pasoh Forest, and these values were used for the present estimation of long-term evapotranspiration. Differences in the plots in Fig. 1(c) mainly appear in the range of large rainfall events. The calculations do not agree with a tendency in the observations that interception linearly increases with rainfall. Under applications of the Rutter model, since evaporation mainly occurs in a rainless period, interception tends to be large for rainfall events of weak intensity and long duration, including rainless periods. Therefore, the calculated interception is liable to be small under a tropical rain forest climate characterized by heavy storms within short durations. Therefore, the disagreement in Fig. 1(c) may suggest more intense evaporation during and after a rainfall event though it is difficult to explain with our model framework. However, the observations may include some errors during a big storm with very intense rainfall. More careful and more detailed observation may be necessary to detect the cause of the disagreement.

Long-term evapotranspiration

Long-term evapotranspiration from the Pasoh Forest was estimated using the Penman-Monteith-Rutter model application. The meteorology, evapotranspiration and their annual amounts from 1995 to 1999 are shown in Figs 3 and 4, and Table 1. Figure 4 displays both the results of interception calculated using two values for the saturation storage capacity on the canopy (*S*), 0.74 mm and 1.5 mm, suggested from Amazonian forest and regarded as the maxima for tropical forests, respectively. The sensitivity of interception to the total evapotranspiration seems small in this figure. This is not only caused by the fact that a larger value of *S* produces a longer period of wet canopy for interception and a shorter period of dry canopy, but also due to the small ratios of interception to total evapotranspiration compared with those under a temperate climate. Therefore S = 1.5 mm was employed in the final estimation in Table 1, although some errors were still included in it.

Figure 5 also shows that the total evapotranspiration occupied a large portion of the net radiation, and that their high ratio did not decrease even in a remarkably dry

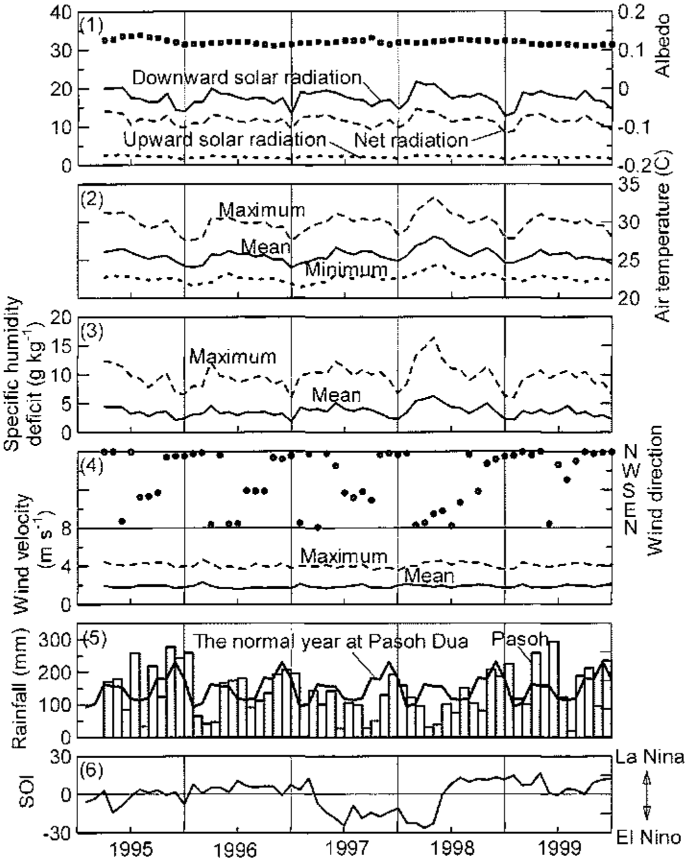

Fig. 3 Seasonal variations in monthly averages of meteorological variables. (1) Daily total of downward and upward solar radiation, net radiation and daily mean albedo. (2) Daily mean, maximum and minimum of air temperature. (3) Daily mean and maximum of specific humidity deficit. (4) Daily vector averaged wind direction and daily mean and maximum of wind velocity. (5) Monthly rainfall at Pasoh Tower and that of the normal year at Pasoh Dua. (6) Southern Oscillation Index (SOI).

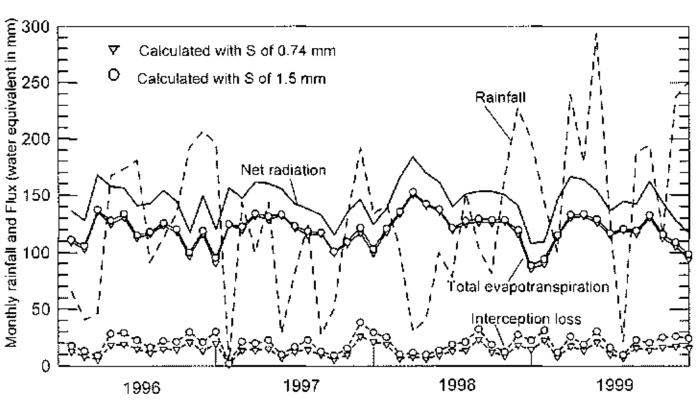

Fig. 4 Estimation results of monthly evapotranspiration with observed monthly rainfall and net radiation.

Table 1 Annual evapotranspiration in the Pasoh Forest (mm).

Year	Rainfall	Net radiation	Interception	Transpiration	Total evapotranspiration	ET/NR
1996	1610	1721	261	1146	1407	82%
1997	1182	1715	220	1218	1438	84%
1998	1426	1821	222	1309	1531	84%
1999	2065	1717	264	1152	1416	82%
Mean	1571	1744	242	1206	1448	83%

The values of energy flux are converted to those in water equivalent using latent heat for vaporization.

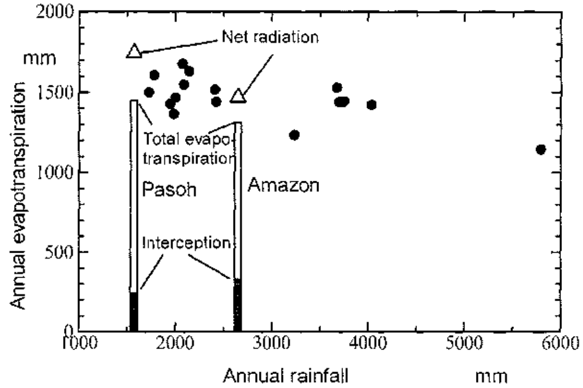

Fig. 5 Comparison of annual evapotranspiration estimated by micro-meteorological observation with that calculated from the catchment water budget. Bar: micro-meteorological observation with net radiation (Δ), ●: catchment water budget after Bruijnzeel (1990).

condition due to the El Niño in 1997 and 1998. The mean ratio of 0.83 (Table 1) was smaller than that of 0.90 for Amazonian rain forest (Shuttleworth, 1988) but the characteristics seems to be common to both forests considering the small rainfall conditions during our observation period. Indeed, the mean annual total values (water equivalent using latent heat of vaporization) of net radiation and rainfall of 1744 and 1571 mm in Pasoh during our observation period indicate a fairly dry climate compared with the corresponding values of 1469 and 2599 mm for the Amazon (annual mean values averaged from October 1983 to September 1985 in Shuttleworth, 1988). Nevertheless, the annual evapotranspiration for Pasoh was 1448 mm, larger than the 1311 mm determined for the Amazon. Such a large evapotranspiration value may have been sustained by soil water storage supplied by rainfall in the wetter years previous to our observation period. A recent observation in a hill evergreen forest in Thailand with a long and severe dry season from December to March showed a large evapotranspiration value was estimated throughout year (Tanaka *et al.*, 2003). These observation results suggest that evergreen forests in humid tropics may maintain high evapotranspiration rates even in dry seasons and that seasonal variation follows the net radiation. This characteristic found first in the Amazonian forest may occur widely in tropical rain forests with smaller rainfall amounts.

Relationships of annual evapotranspiration to annual rainfall estimated from micro-meteorological observations in Pasoh and the Amazon are plotted with net radiation in Fig. 5, which demonstrates the relationships obtained from catchment water budget observations in tropical lowland forests (Bruijnzeel, 1990). The two micro-meteorological results fall within a small range of evapotranspiration values given by many catchment studies with large variations of rainfall. In addition, both of them are plotted at the lower range of the water budget values. This may be plausible because a catchment water budget is obliged to overestimate evapotranspiration in the case of runoff underestimation caused by deep percolation. Therefore, this comparison supports our result that evapotranspiration accounted for a large portion of the net radiation.

Acknowledgements We thank the Forestry Department of Negeri Sembilan and Director General of FRIM for giving us permission to work in the Pasoh Forest Reserve, and Prof. M. Suzuki of the University of Tokyo and Dr H. Takizawa of Nihon University for their information. The staff of the Hydrology Unit and Pasoh Station of FRIM is acknowledged for collecting data. This study was conducted as part of a joint research project between the Forest Research Institute Malaysia, Universiti Putra Malaysia and National Institute for Environmental Studies (Global Environment Research Program granted by Ministry of the Environment, Japan).

REFERENCES

Bruijnzeel, L. A. (1990) *Hydrology of Moist Tropical Forest and Effects of Conversion: A State-of-Knowledge Review.* UNESCO-IHP, Paris, France.

Calder, I. R., Wright, I. R. & Murdiyarso, D. (1986) A study of evaporation from tropical forest—West Java. *J. Hydrol.* **89**, 13–30.

Jetten, V. G. (1996) Interception of tropical rain forest: performance of a canopy water balance model. *Hydrol. Processes* **10**, 671–685.

Kato, R., Tadaki, Y. & Ogawa, F. (1978) Plant biomass and growth increment studies in Pasoh Forest. *Malay. Nat.* **30**(2), 211–224.

Lloyd, C. R., Gash, J. H. C., Shuttleworth, W. J. & Marques, F. A. de O. (2003) The measurement and modeling of rainfall interception by Amazonian rainforest. *Agric. For. Met.* **43**, 277–294.

Manokaran, N. (1979) Stemflow, throughfall and rainfall interception in a lowland tropical rain forest in Peninsular Malaysia. *The Malaysian Forester* **42**(3), 174–201.

Shuttleworth, W. J. (1988) Evaporation from Amazonian rainforest. *Proc. Roy. Soc. B* **233**, 321–346.

Tanaka, K., Takizawa, H., Tanaka, N., Kosaka, I., Yoshifuji, N., Tantasirin, C., Piman, C. & Suzuki, M. (2003) Transpiration peak over a hill evergreen forest in northern Thailand in the late dry season: assessing the seasonal changes in evapotranspiration using a multi-layer model. *J. Geophys. Res.* (in press).

Tani, M., Abdul Rahim, N., Ohtani, Y., Yasuda, Y., Mohd, Md S., Baharuddin, K., Takanashi, S., Noguchi, S., Zulkifli, Y. & Watanabe, T. (2003) Characteristics of energy exchange and surface conductance of a tropical rain forest in Peninsular Malaysia. In: *Pasoh: Ecology and Natural History of a Lowland Tropical Rain Forest in Southeast Asia* (ed. by T. Okuda, K. Niiyama & S. C. Thomas). Springer, Tokyo, Japan (in press).

Yasuda, Y., Ohtani, Y., Watanabe, T., Okano, M., Yokota, T., Liang, N., Tang, Y., Abudl Rahim, N., Tani, M. & Okuda, T. (2003) Measurement of CO_2 flux above a tropical rain forest at Pasoh in Peninsular Malaysia. *Agric. For. Met.* **114**, 235–244.