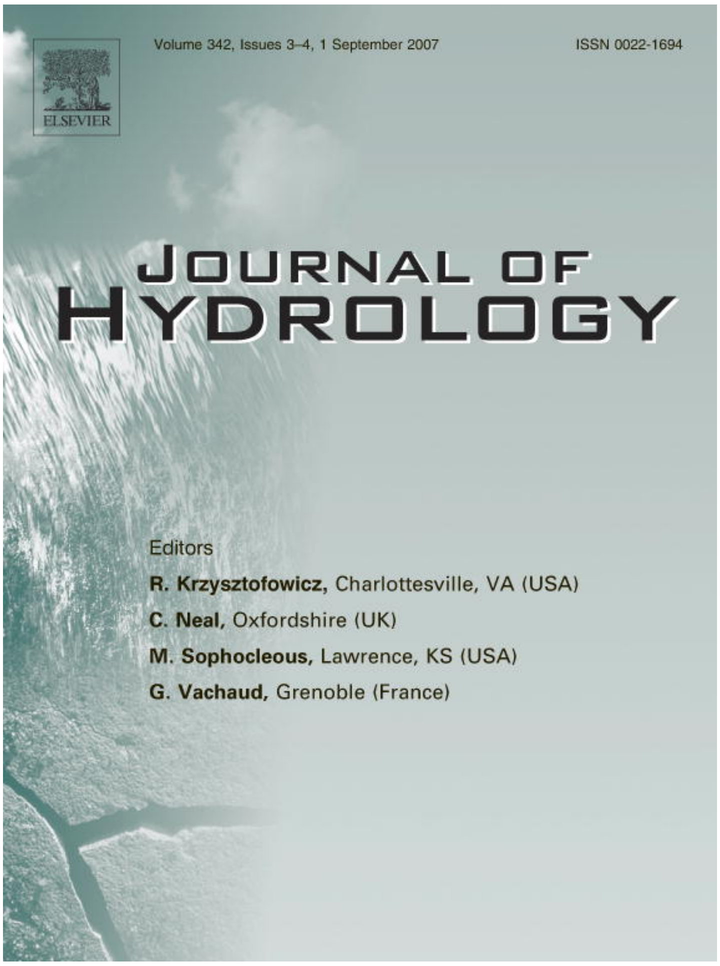
Volume 342, Issues 3–4, 1 September 2007
ISSN 0022-1694
ELSEVIER
JOURNAL OF
HYDROLOGY
Editors
R. Krzysztofowicz, Charlottesville, VA (USA)
C. Neal, Oxfordshire (UK)
M. Sophocleous, Lawrence, KS (USA)
G. Vachaud, Grenoble (France)

Journal of Hydrology (2007) **342**, 305–319

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Application of three canopy interception models to a young stand of Japanese cypress and interpretation in terms of interception mechanism

Shigeki Murakami *

Tohkamachi Experimental Station, Forestry and Forest Products Research Institute, Tatsu-Otsu 614, Tohkamachi-shi, Niigata-ken 948-0013, Japan

Received 7 September 2006; received in revised form 30 May 2007; accepted 30 May 2007

KEYWORDS
Canopy interception;
Rainfall intensity;
Gash model;
Splash;
Raindrop

Summary Three canopy interception models were applied to a stand of young Japanese cypress to obtain a better understanding of the dependence of canopy interception on rainfall intensity (DOCIORI) and the mechanism of splash droplet evaporation (SDE). The applied models were the heat budget model, the newly proposed DOCIORI model, and the revised Gash model. The heat budget model underestimated observed interception by 62.9% in 1999 and 63.4% in 2000; these amounts could be regarded as approximately equal to the amount of SDE. Canopy interception comprises SDE and evaporation from the canopy surface, but the heat budget model calculates evaporation only from the canopy surface. Estimates derived from both the DOCIORI model and the revised Gash model are consistent with observed interception; these models are mathematically equivalent. Reanalysis of previously published data yielded DOCIORI values for interception sites in Spain, Puerto Rico, and the USA. In addition, the relation between mean rainfall intensity and mean evaporation rate calculated using the original and revised Gash models was examined using combined data from the present study and previously published studies; a positive correlation was found between the two values especially in the areas where the rainfall intensity is high. These results support the proposal that DOCIORI and SDE are universal phenomena especially in the high rainfall intensity areas. As literature data indicate that mean evaporation rate is independent of tree height and leaf area index, it can be concluded that canopy interception is mainly governed by rainfall regime rather than forest architecture in the high rainfall intensity areas.

* Tel.: +81 25 752 2360; fax: +81 25 752 7743.
E-mail address: smura@ffpri.affrc.go.jp

0022-1694/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2007.05.032

Introduction

Canopy interception is a function of canopy structure, rainfall regime and climatic variables. Among those factors Murakami (2006) focused on rainfall regime, especially rainfall intensity and revealed that canopy interception loss is clearly proportional to rainfall intensity in a young stand of Japanese cypress, which was termed the dependence of canopy interception on the rainfall intensity (DOCIORI). This phenomenon can be explained by evaporation from splash droplets that are produced when raindrops intercept the canopy (Murakami, 2006). As both the number of raindrops and their size increase with increasing rainfall intensity (Marshall and Palmer, 1948), so does the kinetic energy of the raindrops. This in turn acts to increase the number of splash droplets, which promotes evaporation from their surfaces due to their large combined surface area.

A conventional heat budget method such as the Penman–Monteith equation (Monteith, 1965) is unable to explain DOCIORI because it does not include rainfall intensity as input data and/or parameters. The Rutter model (Rutter et al., 1971, 1975) that includes a conventional heat budget component also cannot explain DOCIORI. The heat budget approach considers evaporation from the canopy surface but not from splash droplets. This commonly leads to underestimates of canopy interception and/or evaporation during rainfall, especially at sites with high rainfall intensity (Calder et al., 1986; Schellekens et al., 1999; Iida et al., 2005). The other major canopy interception models are the original Gash model (Gash, 1979) and its revised version (Gash et al., 1995). The three primary aims of the present study are concerned with the application of three canopy interception models: the heat budget model, the new DOCIORI model, and the revised Gash model. The first aim is to estimate the percentage of splash droplet evaporation (SDE) using the conventional heat budget model for a wet surface that considers evaporation only from the canopy surface. The difference between observed and estimated canopy interception using the heat budget model is expected to represent the difference between the total canopy interception and evaporation from the canopy surface, i.e., evaporation by splash droplets. Toba et al. (2006) applied this approach and conducted a canopy interception experiment using imitation Christmas trees of 60 cm in height and an artificial rainfall simulator to estimate the amount of splash droplet. The amount of splash droplet (termed 'mist' in their study) M was estimated from the measurement of rainfall for the rain event P_G, net rainfall TS, evaporation from the canopy surface $E\tau$ (using the Penman–Monteith equation), and water storage on the canopy 10 min following the cessation of rainfall d. Where E is the mean evaporation rate from the canopy during rain event, τ is the duration of the rain event

$$M = P_G - \mathrm{TS} - E\tau - d \qquad (1)$$

P_G was measured using a raingauge, TS was collected on a tray and measured using a tipping bucket, d was measured by weighing the tree with an electric balance, and $E\tau$ was estimated via the Penman–Monteith equation by conducting micrometeorological observations above the canopy. The experiments were conducted for four different values of plant area index (PAI): 9.1, 7.2, 4.5, and 2.7. The PAI was changed by cutting leaves and branches from the trees. The authors concluded that the amount of splash droplet represented approximately 60% of total canopy interception. The authors also pointed out that M increased with rainfall intensity but was independent of PAI. Validity of this estimation is evaluated in the present study.

The second aim is to interpret the Gash models in terms of DOCIORI. The third aim of the study is to assess the universality of DOCIORI and SDE by highlighting the limitations of the heat budget model, mainly based on a literature review. The relationships between vegetation height, leaf area index (LAI), and mean evaporation rate during rainfall are also discussed.

Study site and observation data

Canopy interception was observed from 1999 to 2000 within a stand of young Japanese cypress (*Chamaecyparis obtusa*) that was planted in 1988 at the Hitachi Ohta Experimental Watershed on the Pacific coast of eastern Japan (latitude 36°34′ N, longitude 140°35′ E; altitude: 320 m; Murakami et al., 2000; Murakami, 2006). Total dimension of the stand is 13.2 ha that comprises of Japanese cedar (*Cryptomeria japonica*, areal ratio of 12%) and *C. obtusa* (88%). Annual precipitation was 1707.9 mm and 1452.9 mm in 1999 and 2000, respectively, with annual average precipitation of 1467.7 mm for the period 1991–2000. Winter is the dry season in this area, and snowfall was 34.3 mm and 21.3 mm in 1999 and 2000, respectively.

Average tree height and average diameter at breast height (DBH) were 5.8 m and 7.0 cm in May 1999, and 6.3 m and 8.1 cm in October 2000, respectively. LAI measured in 2000 using a LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE, USA) changed seasonally from 3.9 to 5.7. The stand density was 2944 stems per hectare, and the canopy was almost closed.

Throughfall was collected using two troughs of 590 cm in length and 18 cm in width, and stemflow collectors were set at eight trees. The area of the canopy interception plot was 29.63 m^2. Throughfall and stemflow flowed into separate tanks, and both tanks were drained automatically once the collected water reached the maximum level. Throughfall and stemflow were then calculated from the changes in water level in the tanks with the resolutions of 0.1 mm and 0.07 mm, respectively. Two raingauges were installed within open areas at the ground level in the watershed. One had the resolution of 0.5 mm installed at the clearing of some 4 m in radius (about 170 m away from the canopy interception plot), and another, which was at a meteorological station described later, had that of 0.1 mm installed at the clearing of about 3 m in radius. Since both the raingauges were located at the ridges (Fig. 1 of Murakami, 2006) the effects of trees on the measurements were small in spite of small clearing radii. Rainfall was considered to be a single rain event in the case that rainfall was not observed for a period of more than 6 h following the cessation of the rainfall event of interest. If rainfall of the single rain event was less than 5.0 mm the data obtained by the raingauge with the resolution of 0.1 mm was employed, and if rainfall was more than or equal to 5.0 mm the averaged data of the two raingauges was regarded as gross precipitation and used to calculate canopy interception. The meteorological station was also established within the open area in the watershed, some 20 m from the interception site. Using the instruments manufactured by Ikeda Keiki Seisakusho, air temperature and relative humidity RH (HM-202S, thermistor and film polymer sensor), wind speed and direction (KS82P) and global solar radiation (SR-180) were measured at 10-min intervals.

The Mito Meteorological Observatory (36°23′ N, 140°28′ E, 29 m above sea level, 25 km southwest of Hitachi Ohta) whose RH data were used in Section ''Heat budget model'' is one of the Meteorological Observatories of the Japan Meteorological Agency, a government organization. They measure air temperature, RH, air pressure, precipitation, wind speed, wind direction, sunshine duration and snow depth automatically. In addition to it, observation of cloud, atmospheric phenomenon, weather and measurement of visibility are conducted manually four times per day. RH is measured using Vaisala HMP 233 that can measure RH within ±2% for $90\% \leqslant RH \leqslant 100\%$, and ±1% for $0\% \leqslant RH \leqslant 90\%$. The sensor is installed in a ventilated cylinder with a wind speed of 4 m s^{-1} and is calibrated every month.

Models

Three models were applied to the *C. obtusa* stand: a conventional heat budget model, a newly constructed DOCIORI model, and the revised Gash model. Both the heat budget model and the DOCIORI model are constructed from the same backbone model (Section ''Backbone model'') and are applied on a rain-event basis. The heat budget model, which is outlined in Section ''Heat budget model'', has already been applied to the Hitachi Ohta Experimental Watershed (Murakami et al., 2000), while the DOCIORI model is described in Section ''DOCIORI model''. The revised Gash model is outlined in Section ''Revised Gash model'' and finally, the interrelations and the interpretations of the models are considered in Section ''Interrelations and interpretations of the models''.

Backbone model

The background equations that are common to both the heat budget model and the DOCIORI model are explained in this section. These equations are termed the backbone model, and are based on the work of Kondo et al. (1992). The backbone model considers discrete rainfall events, and it is assumed that each of the events consists of one or two evaporation processes, depending on storm size. For a small rain event that does not saturate the canopy, only one stage is considered, whereas two stages are considered for a large event that saturates the canopy or the canopy and the tree trunks.

For a small rain event, when the inequality $c^*P_G < E\tau + S_{max}$ presented in Eq. (2) is satisfied, the evaporation rate from the canopy and water stored on the canopy and the tree trunks are larger than the capture rate of raindrops. In this case, all the water caught by the canopy and the tree trunks evaporates and canopy interception I is written as

$$I = c^*P_G \quad \text{for } c^*P_G < E\tau + S_{max} \tag{2}$$

where c^* is the chance of a raindrop hitting the canopy and S_{max} is the total water storage capacity of the canopy and the tree trunks. That is, $S_{max} = S + S_t$, where S is water storage capacity on the canopy and S_t is the trunk storage capacity. The specific methods used to calculate E are described in Sections ''Heat budget model'' and ''DOCIORI model''.

For a large rain event, when the inequality $c^*P_G \geqslant E\tau + S_{max}$ shown in Eq. (3) is satisfied, two canopy interception processes should be taken into account: evaporation during rainfall and evaporation once the rain ceases. Thus, I is written as

$$I = E\tau + S_a \quad \text{for } c^*P_G \geqslant E\tau + S_{max} \tag{3}$$

where S_a is the water stored within the canopy and the trunks immediately following the rainfall event. At the initial stage of rainfall leaves and branches are wetting up and dripping begins. Dripping water is wetting up lower leaves and branches or reaches the forest ground directly. A longer period of rainfall is wetting up the trunks and this makes S_a larger. As S_a increases with P_G, it is assumed that S_a is proportional to P_G for a small amount of rainfall and that S_a approaches S_{max} with rainfall. Similarly, c^* approaches c (canopy closure, $0 \leqslant c \leqslant 1$) with F (the leaf inclination factor, set at 0.5 in this study) and LAI. S_a and c^* are assumed to be written as

$$S_a = S_{max}[1 - \exp(-P_G/S_{max})] \tag{4}$$

$$c^* = c[1 - \exp(-FLAI/c)] \tag{5}$$

The value of c was determined from a tree survey, and S was estimated from the relation between throughfall and rainfall for rain events with minimal evaporation during rainfall (Leyton et al., 1967). The forest parameters c are 0.81 and 0.94, and S are 0.41 mm and 0.44 mm, respectively, for the years 1999 and 2000. The values of S are different from those of Murakami (2006), 0.5 mm in 1999 and 0.7 mm in 2000, which were based on the preliminary analysis. The values of S_t were 0.19 mm in 1999 and 0.13 mm in 2000, which were estimated from the relation between stemflow and rainfall. LAI was assumed to be constant at 4.5, which is the average value for 2000. The heat budget model and the DOCIORI model are developed on the basis of this backbone model, as described in the following two sections.

Heat budget model

E in Eqs. (2) and (3) was calculated in terms of the heat budget equation and the transfer equations. Total incident radiation R_n, which canopy surface absorbs, comprises of three components

$$R_n = (1 - \text{ref})S^{\downarrow} + L^{\downarrow} - \sigma T_s^4 \tag{6}$$

where ref is the surface albedo, $S^{\downarrow}$ is the downward solar radiation and $L^{\downarrow}$ is the downward longwave radiation, σT_s^4 is the upward longwave radiation, σ is Stefan–Boltzmann constant, and T_s is canopy surface temperature. R_n is partitioned into sensible heat flux H, latent heat flux λE and soil heat flux G , where λ is the latent heat of vaporization

$$R_n = H + \lambda E + G \tag{7}$$

H and E can be expressed by the transfer equations

$$H = \frac{c_p \rho}{r_a}(T_s - T_a) \quad (8)$$

$$E = \frac{\rho}{r_a}(q_{sat}(T_s) - q(T_a)) \quad (9)$$

where c_p is the specific heat of air at constant pressure, ρ is air density, T_a is air temperature, r_a is aerodynamic resistance, q_{sat} is the saturated specific humidity, q is specific humidity. The aerodynamic resistance r_a was estimated using the logarithmic boundary layer equation:

$$r_a = \frac{1}{\kappa^2 u}\left[\ln\left(\frac{z-d}{z_0}\right)\right]^2 \quad (10)$$

where κ (=0.4) is von Karman's constant, u is wind speed at the reference height z, d is the zero plane displacement, and z_0 is the roughness length. The relations $d = 0.78h$ and $z_0 = 0.07h$, where h is tree height (Hattori, 1985), were used. Wind speed measured at the meteorological station (Section ''Study site and observation data'') was used and $z = h + 1$m, neutral stability and equal conductance for heat and momentum were assumed.

Both the downward and the upward longwave radiation were estimated and used on a daily basis. Downward longwave radiation was estimated from air temperature, relative humidity, and daily sunshine hours (Kondo et al., 1991). Upward longwave radiation was calculated from the Stefan–Boltzmann law using numerically calculated canopy surface temperature from Eqs. (7)–(9). ref and G were set at 0.1 and zero, respectively. A hygrometer stationed at the study site failed to accurately measure humidity during rain events. A high-polymer hygrometer was used (Section ''Study site and observation data''), however, the measurable range is limited to less than humidity values of 95%. For this reason, monthly average humidity during rain events (hourly average) recorded at the Mito Meteorological Observatory (Section ''Study site and observation data'') was used in the present calculations. In employing the heat budget approach, evaporation from the canopy surface can be calculated using Eqs. (2)–(10): Eqs. (7)–(9) were solved numerically.

DOCIORI model

E in Eqs. (2) and (3) is estimated based on DOCIORI. Murakami (2006) analyzed rain events with rainfall of more than 20 mm and found that hourly canopy interception loss is proportional to hourly rainfall during a rain event (Fig. 2 of Murakami, 2006) that could be explained by SDE. The inclination of this regression line is defined as DOCIORI, i (dimensionless). Therefore, the hourly evaporation rate from the canopy for the rain event is estimated as ip_g, where p_g is hourly rainfall (rainfall intensity). Since E is defined as evaporation rate from the canopy, ip_g and E are equivalent:

$$E = ip_g \quad (11)$$

E includes evaporation from both the canopy surface and splash droplets. The goal of this section is to generalize and formulate i.

i shows seasonal variation (Figs. 2 and 3a in Murakami, 2006), with DOCIORI reaching a maximum in summer. Data shown in Fig. 3a of Murakami (2006) was superimposed for the years 1999 and 2000 and approximated as a function of the day of the year (DOY), as shown in Fig. 1. The curved line in Fig. 1 is the regression sine curve that fits all data points except three (arrowed) that show extraordinary values. The cause of these outlying points could be attributed to the hydrometeorological variability during rain events such as variations in vapor pressure deficit (VPD). Though SDE seems to be an important mechanism governing canopy interception loss, there are other variables that are important and contributive to variability in losses between different rain events. The sine curve is expressed as

$$i = 0.243\sin(DOY/2.16) - 0.0184 \quad \text{for } 63 < DOY < 326 \quad (12)$$

This sine curve can be applied to DOY between 62 and 325. For the other two periods (DOY smaller than or equal to 63 and larger than or equal to 326), i is assumed to be constant at 0.1, as no observed data were available and the lower distribution limit of i is around 0.1:

$$i = 0.1 \quad \text{for } DOY \leqslant 63 \quad \text{or} \quad DOY \geqslant 326 \quad (13)$$

It is now possible to calculate the hourly evaporation rate during rainfall, ip_g (i.e., E), using Eq. (12) or (13) as a function of DOY, although the applicability of this approach might be limited in the forest stand analyzed in the present study. Thus, canopy interception can be calculated by combining Eqs. (2)–(5), and Eqs. (11)–(13). The actual calculation was carried out on a rain event basis. DOY was fixed to the date of the beginning of the rain event, even if the event lasted for more than one day.

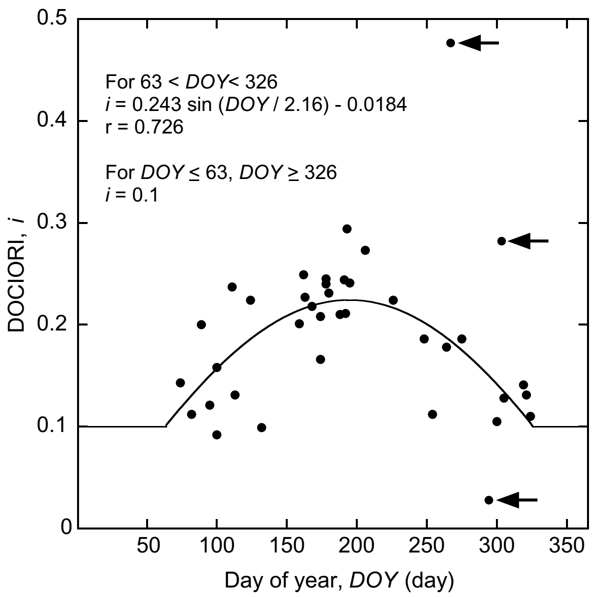

Figure 1 DOCIORI (dependence of canopy interception on rainfall intensity) plotted versus DOY (day of year). The DOCIORI data in Fig. 3a of Murakami (2006) that show two years of data were superimposed annually. The three arrowed data points were excluded from the calculation of the regression curve. The unit of the sine function is degrees.

Revised Gash model

The revised Gash model (Gash et al., 1995) was applied bimonthly for two years. At first the model was applied on an annual basis for the two years (Murakami, 2007), however, the discrepancy between observed and calculated interception was larger than the results of bimonthly analysis in both years. Calculated interception for the two respective years was 0.9% and 13.6% larger than observed interception for bimonthly analysis (Section ''Results''), while was 9.2% and 24.4% larger than observed values for annual analysis. The reason why the accuracy in annual analysis was inferior to in bimonthly could be explained by seasonal changes in E. As seen in Fig. 1 DOCIORI changes with seasons, which suggests E also change with seasons and an analysis on a seasonal basis would be required in stead of annual basis for accurate calculation. For this reason a monthly application was also attempted, but the number of rain events was insufficient in certain months to enable analysis; thus, bimonthly analysis was used. The revised Gash model can be calculated from daily rainfall totals assuming one rain event per day; however, in this study it was employed on a rain-event basis.

The revised Gash model considers a series of discrete rain events, as with the backbone model, and assumes that each rain event comprises three evaporation periods: a period of wetting up under rainfall of less than P'_G, which is the rainfall amount required to saturate the canopy; a period of saturation; and a period of drying following the cessation of rainfall. P'_G is expressed using the mean rainfall rate $\overline{R}$, the canopy capacity per unit area of cover, S_c, and $\overline{E}_c$, the mean evaporation rate during rainfall from the canopy cover:

$$P'_G = -\frac{\overline{R}S_c}{\overline{E}_c}\ln\left[1-\left(\frac{\overline{E}_c}{\overline{R}}\right)\right] \quad (14)$$

The bars on $\overline{R}$ and $\overline{E}_c$ represent the mean for a time t, the time from canopy saturation to the end of the rain event. $\overline{R}$ can be expressed as $\overline{R} = (P_G - P'_G)/t$, and is approximately equal to the average of p_g for rain events where P_G is large in comparison with P'_G. S_c is expressed as $S_c = S/c$: the values of S_c are 0.51 mm in 1999 and 0.47 mm in 2000. $\overline{E}_c$ can be written as $\overline{E}_c = \overline{E}/c$, and $\overline{E}$, the mean evaporation rate during rainfall, can be calculated by multiplying $\overline{R}$ by a, the inclination of the regression line between P_G and I, on a bimonthly basis (see Section ''Basic equation between the backbone model and the Gash models'' and ''Results''). The values τ and t are largely equivalent for the purpose of this study (Section ''Basic equation between the backbone model and the Gash models''), though their physical meanings are different. $\overline{E}$ and E are also approximately equal if equivalent time scales are considered.

Depending on the threshold rainfall P'_G, the canopy evaporation scheme is categorized into the four following processes:

1. Evaporation for m number of storms that do not saturate the canopy ($P_G < P'_G$)
2. Evaporation for n number of storms that wet-up the canopy to saturation ($P_G \geqslant P'_G$)
3. Evaporation from the saturated canopy during rainfall
4. Evaporation once rainfall ceases

In addition to these four processes, evaporation from trunks is also considered once the canopy is saturated; this can be estimated as follows from the amount of rainfall:

1. Evaporation for q number of storms that saturate tree trunks ($P_G \geqslant S_t/p_t$)
2. Evaporation for $n - q$ number of storms that do not saturate tree trunks ($P_G < S_t/p_t$)

p_t is the portion of rain water diverted to stemflow. The values of p_t were 0.042 in 1999 and 0.050 in 2000.

Interrelations and interpretations of the models

In this section the similarities and differences in the backbone, the heat budget, and the DOCIORI models are discussed in terms of the Gash models.

Basic equation between the backbone model and the Gash models

Both the original and the revised Gash models include $\overline{E}$, while the backbone model has a similar variable E. $\overline{E}$ and E, and t and τ are largely equal, respectively, as described in the previous section. The aim of this section is to organize these relations mathematically, and to derive an important equation, Eq. (17), from the backbone model, which is a basis for understanding the relation between the backbone model and the Gash models.

The empirical regression equation between rainfall and canopy interception is expressed as

$$I = aP_G + b \quad (15)$$

where a and b are regression constants. Eq. (15) can be used either to describe sets of storm data or to describe one rain event with P_G and I as variables. Comparing Eqs. (3) and (15), the evaporation rate E is written as

$$E = a\left(\frac{P_G}{\tau}\right) \quad (16)$$

As $P_G \approx P_G - P'_G$, and $\tau \approx t$ for large values of P_G, therefore, $(P_G/\tau) \approx (P_G - P'_G)/t = \overline{R}$. As a and b are mainly controlled by large values of P_G for sets of storm data, this approximation is valid; consequently:

$$\overline{E} = a\overline{R} \quad (17)$$

Eq. (17), which is shown in Gash (1979), is also derived from the backbone model using approximation. This means that Eq. (17) is effective for the Gash models, the heat budget model and the DOCIORI model.

Contradiction of the heat budget model

Eq. (17) states that the mean evaporation rate during rainfall $\overline{E}$ is proportional to the mean rainfall intensity $\overline{R}$ via the coefficient of proportion a. However, the heat budget model does not include rainfall intensity as a variable (Eqs. (7)–(9)) and cannot explain the physical meaning of Eq. (17) that is understandable by introducing the idea of the SDE. Forest hydrologists have not regarded Eq. (17) as it is: as the proportional relation between $\overline{E}$ and $\overline{R}$. If they had interpreted Eq. (17) to the letter, they could have noticed the contradiction of Eq. (17) concerned with the heat budget or could have obtained linear relation between $\overline{E}$ and $\overline{R}$ as shown by Tsukamoto et al. (1988) and Murakami (2006). Even though some of them had obtained enough data to reveal the proportional relation between $\overline{E}$ and $\overline{R}$, that is, DOCIORI, they did not notice it (Section ''Is DOCIORI universal ?''). Actually, there are mainly two causes to prevent the right interpretation of Eq. (17). For one thing, usual analysis of canopy interception is conducted on a rain-event basis since many canopy interception models are constructed so that they can be applied on a rain-event basis. Taking a time average of $\overline{E}$ and $\overline{R}$ over one rain event is often too long to detect DOCIORI. To make the matter worse, in many cases for the application of the Gash models $\overline{E}$ and $\overline{R}$ are calculated as an average of a series of rain events for longer periods, typically, a few months. Instead, an hourly or shorter period of analysis is suitable because the rainfall intensity varies within much shorter time span than that of one rain event. For another, the SDE would not be always dominant canopy interception mechanism especially in the area where rainfall intensity is weak, which makes DOCIORI undetectable.

Relation between the DOCIORI model and the Gash models

Though both the original and revised Gash models are derived based on the physical processes of canopy interception, the application of these models do not necessarily require meteorological data above canopy that the Rutter model (Rutter et al., 1971, 1975) or the heat budget model (Section ''Heat budget model'') does. In this respect, the Gash models resemble the DOCIORI model that does not require meteorological data above canopy but the values of i and p_g (Section ''DOCIORI model''). The DOCIORI model is very simple but is as much reproducible as the revised Gash model that is constructed based on the physical processes (Section ''Results''). This implies that the evaporation processes considered in the Gash models are built-in in the DOCIORI model as an integrated form. The aim of this section is to clarify the relation between the DOCIORI model and the Gash models mathematically.

The following relation is derived from the definition of the DOCIORI model:

$$E\tau = \sum(ip_g) \tag{18}$$

The summation to the right of the equation is made for hours of rainfall. As i is independent of rainfall hours, it can be removed from the summation. As $\sum p_g = P_G$, Eq. (18) is expressed as

$$E\tau = iP_G \tag{19}$$

Insertion of Eq. (19) into Eq. (3) gives

$$I = iP_G + S_a \tag{20}$$

If we regard $a = i$ and $b = S_a$, Eq. (20) has the same form as Eq. (15) that is the basis of the Gash models; accordingly, the Gash and the DOCIORI models are equivalent. Forest hydrologists have therefore employed the Gash models without knowing that DOCIORI is considered within the models.

Results

Precipitation events whose corresponding values of interception were negative due to measurement error, occult precipitation or which were inferred to be snowfall were not included in the analysis. Consequently, the annual rainfall amounts used for the analysis, which are defined as the effective annual rainfall, were 1673.3 mm for 1999 and 1365.0 mm for 2000; annual observed precipitation was 1707.9 mm for 1999 and 1452.9 mm for 2000, as described in Section ''Study site and observation data''. For effective annual rainfall, canopy interception was 320.1 mm (interception rate: 19.1%) in 1999 and 256.4 mm (interception rate: 18.9%) in 2000.

Canopy interception calculated using the heat budget model was only one-third of the observed value on an annual basis for both 1999 and 2000 (Fig. 2a and b). Calculated and observed values were 118.7 and 320.1 mm for 1999 and 93.9 and 256.4 mm for 2000, respectively. The corresponding values for r_a were $18.6/u$ s m^{-1} in 1999 and $17.8/u$ s m^{-1} in 2000 for tree heights of 5.8 and 6.3 m, respectively. Calculated interception does not increase with increasing observed values: it reaches a plateau at approximately 10 mm.

Canopy interception calculated using the DOCIORI model is in good agreement with observed interception on an annual basis, both for 1999 and 2000 (Fig. 2c and d). Calculated and observed values were 353.5 and 320.1 mm in 1999 and 294.9 and 256.4 mm in 2000, respectively.

The forest parameters c, S, S_c, S_t, and p_t described in the previous section were used for the revised Gash model. These parameters were assumed to be constant through the year. The parameters a, $\overline{R}$, $\overline{E}$, $\overline{E}_c$, and P'_G are listed in Table 1, and were estimated bimonthly. Canopy interception calculated using the revised Gash model is also in good agreement with observed values for both 1999 and 2000 (Fig. 2e and f). Calculated and observed interception were 323.1 and 320.1 mm in 1999 and 291.2 and 256.4 mm in 2000, respectively. Calculated bimonthly and annual components of canopy interception are shown in Table 2 along with effective rainfall and observed canopy interception. The main component of observed canopy interception was evaporation during rainfall, which accounted for 80.1% of total canopy interception during 1999; the equivalent figure for 2000 was 73.9%. On a bimonthly basis, this represents 60.3–86.9% of rainfall, except for January and February in 1999 during which time the rainfall amount was the lowest recorded and evaporation following rainfall was the largest component.

Discussion

Amount of splash droplet evaporation

The difference between observed and calculated canopy interception using the heat budget model is expected to be equal to the amount of splash droplet evaporation. However, much of this assumed SDE could be due to parameter or measurement errors. To assess the potential errors a simple sensitivity analysis was conducted by changing relative humidity RH, $r_a u$ and S_{max}. First, RH was decreased by 5%, though the accuracy of RH sensor

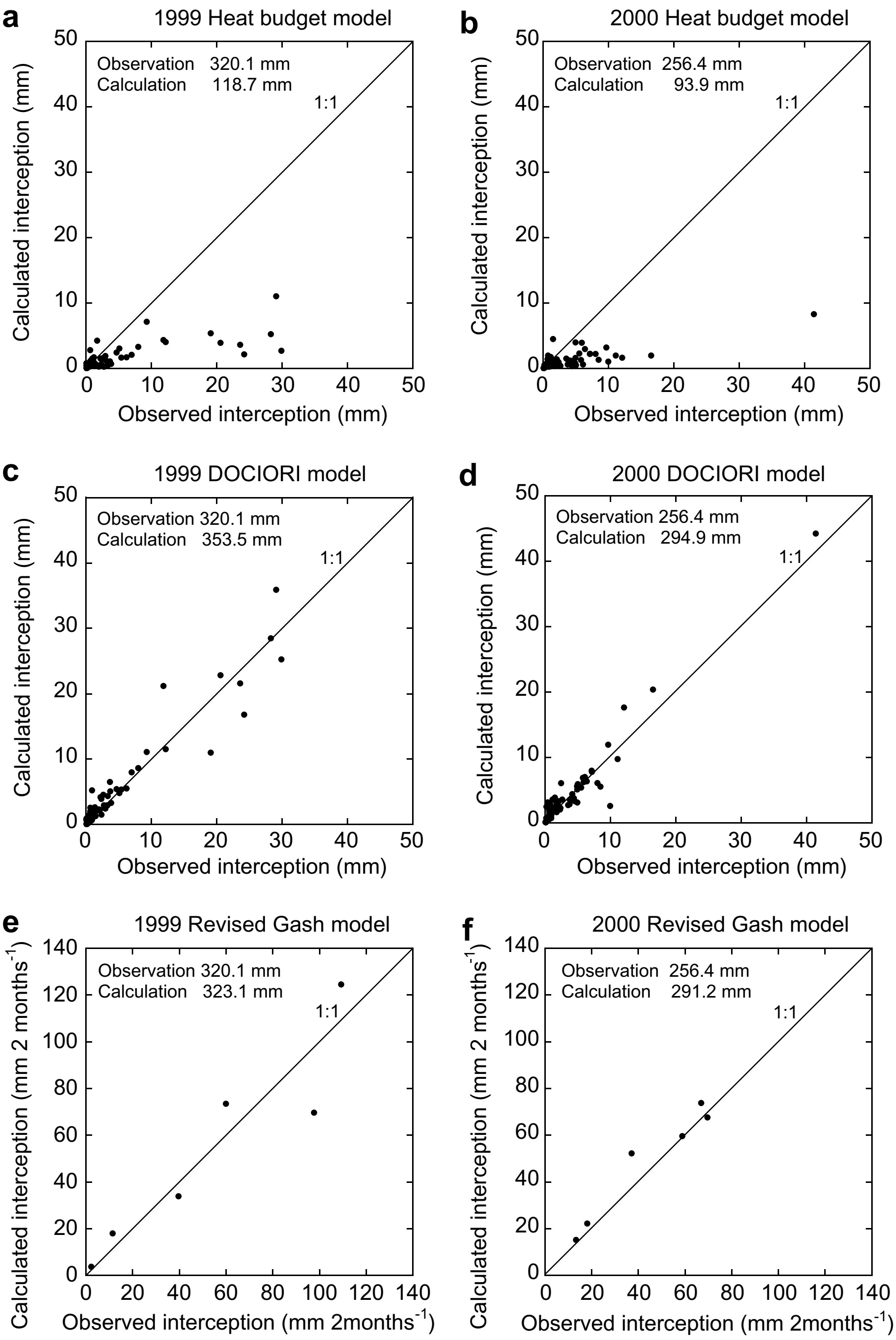

Figure 2 Observed and calculated canopy interception determined using three different models. (a) Heat budget model for 1999. (b) Heat budget model for 2000. (c) DOCIORI model for 1999. (d) DOCIORI model for 2000. (e) Revised Gash model for 1999. (f) Revised Gash model for 2000. (a)–(d) were compiled on a rain-event basis, while (e) and (f) were compiled on a bimonthly basis.

is much better, ±2% for a RH range of 90–100% (Section ''Study site and observation data''). Calculated annual canopy interceptions were 149.6 mm and 119.8 mm for 5% reduction in RH in 1999 and 2000, respectively, which were still underestimation and were less than half of observed annual interceptions of 320.1 mm and 256.4 mm in 1999 and 2000, respectively. Secondly, the values of $r_a u$ were reduced by half, from 18.6 to 9.3 in 1999 and from 17.8 to 8.9 in 2000. These figures correspond to the equivalent tree heights of 58 m and 92 m, respectively, which are unrealistically high in comparison with the actual tree heights. Calculated interceptions were 175.6 mm in 1999 and 131.3 mm in 2000, which were some half of observed values. Thirdly, the values of S_{max} were doubled, from 0.60 mm to 1.20 mm in 1999 and from 0.57 mm to 1.14 mm in 2000, which are larger than expected errors: they are assumed to be several tens of percent at most. Calculated interceptions were 153.9 mm in 1999 and 130.9 mm in 2000 that were about half of observed interceptions of the corresponding years.

Table 1 Bimonthly changes in parameters in Gash model

Parameters	1999						2000					
	January–February	March–April	May–June	July–August	September–October	November–December	January–February	March–April	May–June	July–August	September–October	November–December
a	0.052	0.142	0.244	0.230	0.083	0.107	0.166	0.169	0.168	0.211	0.161	0.189
$\overline{R}$	0.794	1.736	1.610	1.917	1.577	1.024	1.210	1.415	1.039	2.721	1.670	0.621
$\overline{E}$	0.042	0.247	0.393	0.441	0.131	0.110	0.201	0.240	0.174	0.574	0.269	0.117
$\overline{E}_c$	0.052	0.305	0.486	0.545	0.162	0.136	0.214	0.255	0.185	0.611	0.286	0.124
P'_G	0.523	0.557	0.602	0.595	0.534	0.543	0.515	0.516	0.516	0.530	0.513	0.523

Table 2 Observed effective rainfall, observed canopy interception and calculated components of canopy interception by the revised Gash model

	1999							2000						
	January–February	March–April	May–June	July–August	September–October	November–December	Annual	January–February	March–April	May–June	July–August	September–October	November–December	Annual
Effective rainfall (mm)	22.5	426.6	453.9	411.2	274.4	84.8	1673.3	69.8	241.7	350.4	294.8	323.8	84.7	1365.0
Canopy interception (mm)	2.2	59.9	109.3	97.7	39.6	11.4	320.1	13.3	37.1	66.9	58.8	62.2	18.1	256.4
Evaporation for small storms that are insufficient to saturate the canopy (%)	4.7	0.8	0.6	2.8	6.2	4.1	2.0	4.5	1.0	2.3	2.5	2.5	1.7	2.4
Evaporation for storms that wetting-up the canopy to saturate (%)	1.5	0.9	1.1	1.5	0.8	1.2	1.1	1.2	1.1	1.0	1.2	1.0	2.3	1.3
Evaporation from the saturated canopy during rainfall (%)	29.0	80.7	86.9	81.7	65.3	63.5	80.1	73.0	76.0	76.3	81.5	76.4	60.3	73.9
Evaporation after the rainfall ceases (%)	44.9	8.9	5.6	8.2	14.5	16.0	8.9	11.6	11.0	10.1	8.9	10.3	19.8	11.9
Evaporation from the trunks (%)	19.9	8.7	5.9	5.8	13.2	15.2	7.9	9.8	10.9	10.2	6.0	9.8	15.8	10.4

The sum of the components for each period is not necessarily 100% due to the rounding error.

Measurement error can be also derived from the non-above canopy data; the heat budget model should be applied with meteorological data above canopy, but in the present study those obtained above grass, at the clearings or RH data at Mito (Section ''Study site and observation data'') that were also measured above grass, were used. However, this is not the cause of underestimation for the results of the heat budget model in Fig. 2a and b. Pearce et al. (1980) applied the Rutter and the original Gash model for a Scots pine stand, and showed that systematic differences in the meteorological parameters controlling the evaporation rate from wet forest and wet grass are the cause of the overestimation of interception losses when grassland data are used in the models. According to this study the use of the non-above canopy data can yield not underestimation but overestimation. This might be one of the reasons that Murakami et al. (2000) obtained good results for estimation of interception with the heat budget method that were applied for a stand of the same species with an average height of 18 m.

The sensitivity analysis of the heat budget model suggests that evaporation of canopy interception from the canopy surface accounts for about half of total canopy interception at most, though the analysis was conducted focused only on RH, $r_a u$ and S_{max} separately. The assumed amounts of SDE, the differences between observed and calculated canopy interception using the heat budget model are 201.4 mm (=320.1—118.7 mm; 62.9% of observed annual interception) in 1999 and 162.5 mm (=256.4—93.9 mm; 63.4% of observed annual interception) in 2000. These values are consistent with the amount of splash droplet estimated by Toba et al. (2006) described in the Section ''Introduction'', and evaporation estimated using the revised Gash model. Namely, for the revised Gash model the maximum values for SDE are the sum of the three components listed in Table 2: evaporation for small storms that are insufficient to saturate the canopy, wetting up of the canopy, and evaporation from the saturated canopy, yielding values of 83.2% in 1999 and 77.6% in 2000.

Deguchi et al. (2006) demonstrated that seasonal differences in interception loss for a multi-species, deciduous, broad-leaved secondary forest were at most 15.3—22.8%, despite significant seasonal variations in LAI (LAI decreased by 38.9—46.6% from the growing season to the dormant season). The insensitivity of canopy interception to LAI and PAI (Toba et al., 2006, Section ''Introduction'') could be caused by some factors. One is meteorological variability such as RH, wind speed, and rainfall regimes that controls evaporation from both the canopy surface and the splash droplets. Another is the productivity of splash droplets that would not be strongly affected by the amounts of leaves or branches.

Limitations of the heat budget model

Many forest hydrologists have applied the heat budget model, as it is believed to be the most robust and reliable model. However, importantly, a number of workers have noticed that the heat budget model underestimates observed interception despite its underlying principles. In such cases, there are alternatives that can be used to treat the discrepancy between observed and calculated interception.

Calder et al. (1986), in their study in West Java, optimized r_a and used a reduced value of r_a (5 s m^{-1}) at the same time as employing a larger value of S (about 4.5 mm). Schellekens et al. (1999) applied both the Rutter model (Rutter et al., 1971, 1975) and original Gash model to a lowland rain forest in Puerto Rico. The Rutter model, a conceptual model with a heat budget component, underestimated canopy interception for large rain events with estimated $\bar{E}$ of 0.11 mm h^{-1}and S of 1.15 mm. The authors attempted to optimize the parameters of the model by increasing $\bar{E}$ and/or S, and this resulted in improved estimates: the model with larger $\bar{E}$ (2.80 mm h^{-1}) showed a better fit to observed data than the model with larger S (5.75 mm) or larger $\bar{E}$ (1.10 mm h^{-1}) and S (5.75 mm). They also concluded that the claims of very large storage capacities for tropical rain forests (Herwitz, 1985; Calder et al., 1986) are not supported by their analysis.

Iida et al. (2005) applied the Penman—Monteith equation, one of the heat budget models, to a stand of Japanese red pine to estimate evaporation during rain events. The authors then estimated rainfall storage by the tree surface as the difference between observed canopy interception and calculated evaporation during rainfall. Their results show that the storage capacity tends to increase with an amount of rainfall: the maximum storage capacity was estimated at 6.5 mm with a rainfall amount of 50 mm. The authors also claimed that the large storage capacity was reasonable by referring to Herwitz (1985); however, it is unusual that the storage capacity increases with rainfall of until 50 mm. As rainfall intensity increases with rainfall amount, especially for large rainfall events (Kondo et al., 1992), evaporation during rainfall also increases with increasing rainfall because of SDE. Iida et al. (2005) imposed an increase in canopy interception with rainfall amount on the storage capacity, rather than evaporation during rainfall, because their use of the Penman—Monteith equation, which considers evaporation only from the canopy surface, resulted in an underestimate of evaporation during rainfall.

All of the above models underestimated observed interception and/or evaporation during rainfall within study sites in tropical areas or monsoonal Asia where rainfall intensity is often high. These results indicate that SDE may be able to explain the underestimation; in Section ''Is DOCIORI universal?'', it is demonstrated that this is indeed the case.

In the present study, the heat budget model significantly underestimated observed interception, as shown in Fig. 2a and b. An optimization of the simulation was conducted by changing the storage capacity S_{max} or the aerodynamic resistance r_a such that the annual difference between calculated and observed interception reached a minimum. r_a and S_{max} were varied in units of 0.1 s m^{-1} and 0.1 mm, respectively. S_{max} was optimized as shown in Fig. 3a, while r_a was optimized as shown in Fig. 3b. Though annual values agreed within 2.1 mm, canopy interception was overestimated for smaller rain events (for smaller observed canopy interception) and underestimated for larger rain events (for larger observed canopy interception) in both Fig. 3a and b. This trend was not improved even if both r_a and S were varied in tandem for the optimization.

As described by Schellekens et al. (1999), optimization of observed canopy interception using the heat budget model is difficult to implement, especially for large rain events.

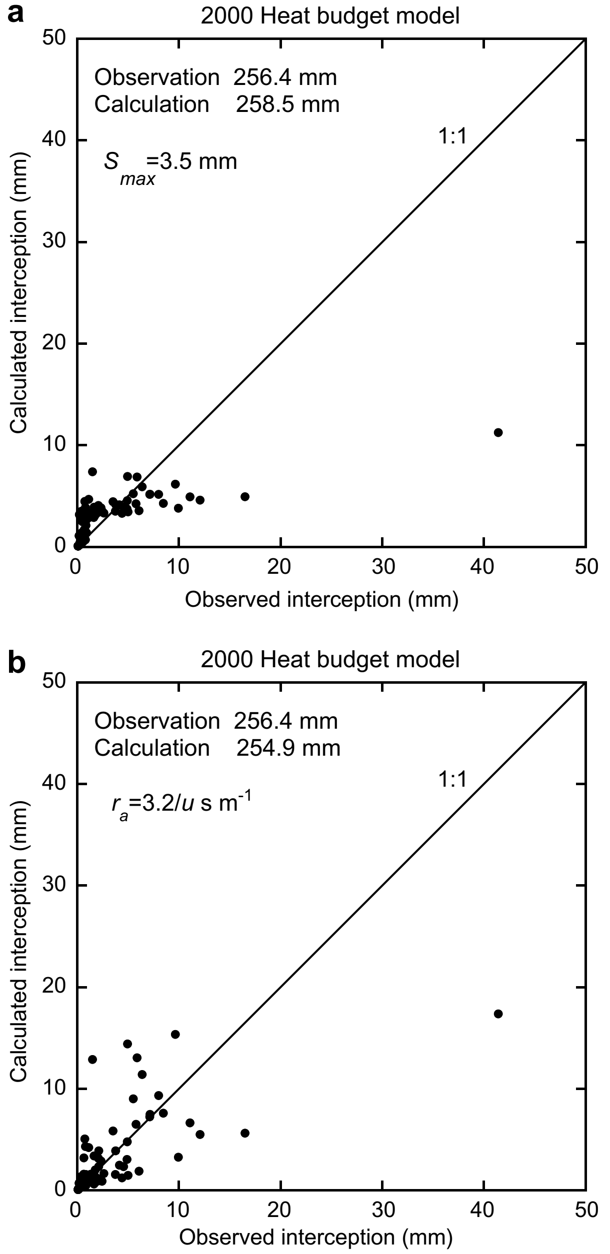

Figure 3 Optimization of the heat budget model. The result shown in Fig. 2b was optimized by changing S_{max} (a) or r_a (b).

If only DOCIORI and SDE are introduced, it is possible to follow the reason for this trend, at least qualitatively. In the following section, the universality of DOCIORI and SDE is discussed, based mainly on a literature review.

Is DOCIORI universal?

Hattori et al. (1982) first described DOCIORI, while Tsukamoto et al. (1988) concluded that evaporation during rainfall is linearly related to rainfall intensity. Murakami (2006) made detailed observations of DOCIORI and proposed a mechanism for this phenomenon by introducing SDE. These three studies were all conducted in Japan. Although no other studies have conclusively demonstrated the phenomenon of DOCIORI, it must have been observed at all interception sites across the globe sufficiently high rainfall intensity.

DOCIORI observed in Puerto Rico, Spain, and the USA

Luckily, Schellekens et al. (1999) conducted observations of canopy interception within a rainforest, as mentioned at the previous section, and their detailed data on rainfall and throughfall at 5-min intervals enables the construction of a chart that shows the relation between rainfall intensity (hourly rainfall) p_g and hourly canopy interception I_h, i.e., DOCIORI. The authors did not obtain stemflow data because it was negligibly small at the site; therefore, the difference between rainfall and throughfall was regarded as canopy interception. Fig. 4a—d was drawn based on Figs. 3a and c and 4a and c of Schellekens et al. (1999). DOCIORI is clearly evident, with a high correlation coefficient in all cases except Fig. 4d. In Fig. 4a—c, which is derived from Schellekens et al. (1999), values of i (0.478—0.625) are much larger than those obtained in the present study (Fig. 1; 0.092—0.294).

Data collected by Llorens et al. (1997) for *Pinus sylvestris* in a Mediterranean mountain region in Spain also reveal DOCIORI, though it was shown on a rain-event basis. The duration of the rain event, VPD, rainfall, and canopy interception are listed in Table 1 of their study. Based on the data, mean hourly rainfall $\bar{P}_G$ is derived from the rainfall amount divided by the rainfall hours, and mean hourly interception $\bar{I}$ represents canopy interception divided by the rainfall hours. It is important to note that each dataset of $\bar{P}_G$ and $\bar{I}$ corresponds to a single rain event that is averaged hourly rather than representing hourly data. In contrast, each panel in Fig. 4 corresponds to a single rain event and p_g and I_h are exactly hourly data. $\bar{I}$ and $\bar{P}_G$ calculated from Table 1 in Llorens et al. (1997) show positive correlations for all three categories. For all the data: $\bar{I} = 0.101\bar{P}_G + 0.179$, $r = 0.778$; for VPD < 1.0 hPa: $\bar{I} = 0.0737\bar{P}_G + 0.4521$, $r = 0.724$; and for VPD $\geqslant$ 1.0 hPa: $\bar{I} = 0.121\bar{P}_G + 0.051$, $r = 0.881$. The regression coefficients provide an indication of i rather than an exact measure, and the positive correlation represents DOCIORI. If you draw the chart you can find that most values of $\bar{I}$ are larger for VPD $\geqslant$ 1.0 hPa than for VPD < 1.0 hPa, though the scatter is large for VPD $\geqslant$ 1.0 hPa. In this dataset the maximum $\bar{P}_G$ is 13.0 mm h^{-1}. Table 3 in Link et al. (2004), whose data were derived from a seasonal temperate rainforest of old-growth Douglas-fir (>450-year-old) in southwestern Washington, USA, also enable to demonstrate the relation between $\bar{I}$ and $\bar{P}_G$. The regression equation is, $\bar{I} = 0.212\bar{P}_G + 0.093$, $r = 0.584$, with the maximum $\bar{P}_G$ of 2.1 mm h^{-1}. The increasing trend of $\bar{I}$ with $\bar{P}_G$ is not apparent with a low correlation coefficient of 0.584. The subsequent work conducted by Pyker et al. (2005) at the 25-year-old Douglas-fir forest, approximately 4 km apart from the old-growth Douglas-fir (Link et al., 2004), also lists the values of I and P_G on a rain-event basis and the regression line can be calculated: $\bar{I} = 0.172\bar{P}_G + 0.098$, $r = 0.728$, with the highest $\bar{P}_G$ of 3.5 mm h^{-1}. Though the value of r is higher than that of the old-growth Douglas-fir, the number of data is only eight, which is much less in comparison with the old-growth Douglas-fir of 43. The increase trend in $\bar{I}$ with $\bar{P}_G$ is not reliable enough in this respect.

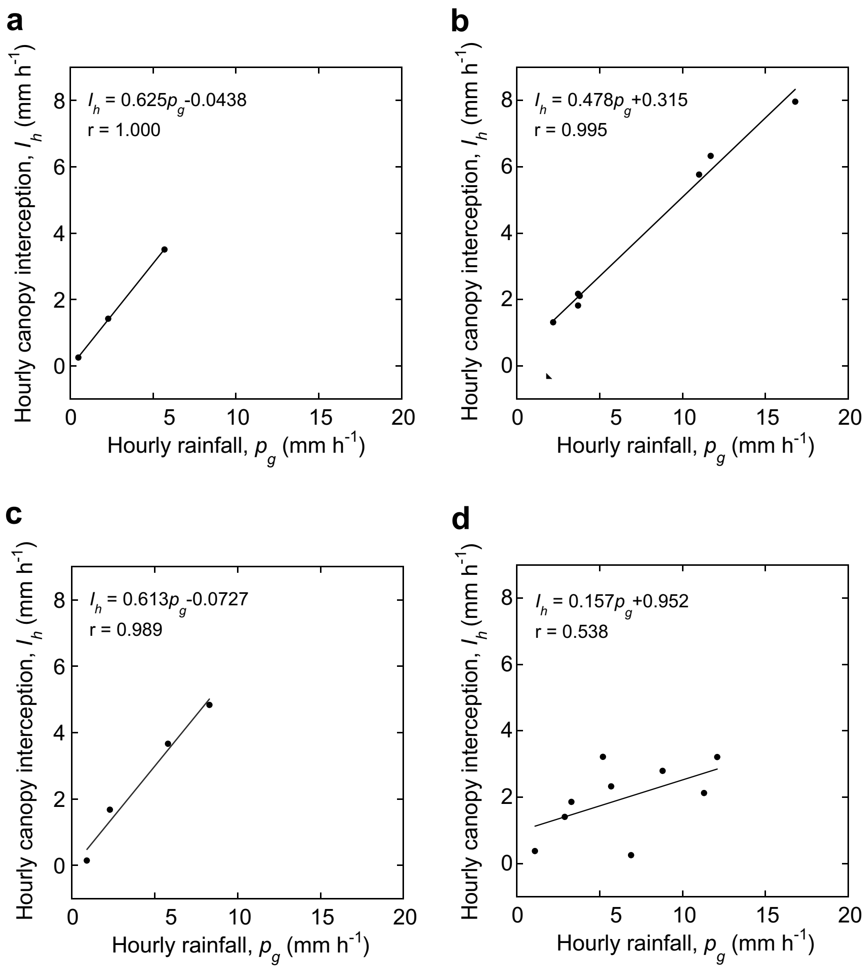

Figure 4 DOCIORI for a tropical rain forest in Puerto Rico. Canopy interception data collected at 5-min intervals (Schellekens et al., 1999) were digitized manually and rearranged into hourly data. (a) Fig. 3(a) of Schellekens et al. (1999). (b) Fig. 3c of Schellekens et al. (1999). Negative interception data (triangle) were excluded when fitting the regression line. (c) Fig. 4a of Schellekens et al. (1999). (d) Fig. 4c of Schellekens et al. (1999).

Although the data used above were obtained from a rainforest in Puerto Rico, a Mediterranean mountain environment, and the USA (rather than Japan), all of the datasets reveal DOCIORI as expected. The presence of DOCIORI in these datasets implies that SDE holds true at sites worldwide. The scatter of data is greater in Llorens et al. (1997), Link et al. (2004), and Pyker et al. (2005) than that in Fig. 4 (and greater than that in Fig. 2 of Murakami, 2006) because the lower time resolution in Llorens et al. (1997), Link et al. (2004), and Pyker et al. (2005) derived from the longer average hours over the duration of the rainfall tends to obscure DOCIORI. It seems that the higher $\overline{P}_G$ or p_g becomes, the more apparent DOCIOR is. The figures of $\overline{P}_G$ or p_g are 43.9 mm h^{-1} (Murakami, 2006), 16.8 mm h^{-1} (Fig. 4), and 13.0 mm h^{-1} (Llorens et al., 1997), which all have relatively higher correlation coefficients with apparent DOCIORI in comparison with 3.5 mm h^{-1} (Pyker et al., 2005) and 2.1 mm h^{-1} (Link et al., 2004). The difference in i or regression coefficients among Fig. 1 (Fig. 2 in Murakami, 2006), Fig. 4, and Llorens et al. (1997), Link et al. (2004), and Pyker et al. (2005) might possibly be explained as the difference in the raindrop size distribution (DSD) among the interception sites in addition to differences in meteorological factors and forest architecture.

Perception of DOCIORI based on Gash models

Detailed data required to demonstrate DOCIORI, such as those collected by Schellekens et al. (1999), Llorens et al. (1997), Link et al. (2004), and Pyker et al. (2005) are rarely available; however, there are many data that show the relation between $\overline{E}$ or $\overline{E}_c$ and $\overline{R}$: many studies that employ Gash models list these values. Some of these studies are reviewed in Table 3, while the regression lines between $\overline{E}$ and $\overline{R}$, and between $\overline{E}_c$ and $\overline{R}$ are calculated, using data obtained in the present study (Table 1) along with previously published data listed in Table 3. For $\overline{E}$ and $\overline{R}:\overline{E} = 0.0716\overline{R} + 0.139$, r = 0.589; for $\overline{E}_c$ and $\overline{R}:\overline{E}_c = 0.0959\overline{R} + 0.109$, r = 0.810. DOCIORI, i, is defined as the inclination of the regression line between I_h and p_g, as shown in Figs. 4 and 2 of Murakami (2006). The regression coefficients in between $\overline{E}$ and $\overline{R}$, and between $\overline{E}_c$ and $\overline{R}$ are not equal to i, but can be regarded as indicators of DOCIORI, as described in Section ''DOCIORI observed in Puerto Rico, Spain, and the USA''.

Table 3 Review of rainfall intensity and evaporation rate calculatd by Gash model

Reference	Commnents	$\bar{R}$	$\bar{E}$	$\bar{E}_c$	LAI	Vegetation hight	Forest or vegitation type	Country
Gash and Morton (1978)		1.38	0.19			18	Scots pine	Great Britain
Gash et al. (1980)		1.75	0.13			8.9	Sitka spruce	Great Britain
		1.22	0.33			15	Scots pine	
		1.37	0.21			12.9	Sitka spruce	
Row (1983)	Summer	2.12	0.53				Evergreen beech forest	New Zealand
	Winter	1.95	0.39					
Dolman (1987)	Summer	1.44	0.32			9.6	Oak forest	The Netherlands
	Winter	1.20	0.11					
Hattori and Chikaarashi (1988)	Before thinning	1.56	0.25		5.7	13.5	Coniferous forest	Japan
	Before thinning	1.54	0.26		5.7	13.5		
	After thinning	1.34	0.17			13.5		
Lloyd et al. (1988)		5.15	0.21			35	Amazonian rain forest	Brazil
Hutjes et al. (1990)		19.99	0.34			24–28	Primary evergreen forest	Cote-d'Ivoire
Loustau et al. (1992)	Summer 1987	1.34	0.15		1.5–4.0	12.6	Pinus pinaster	France
	Winter 1988	1.06	0.07					
	Summer1988	1.34	0.15					
	Winter 1989	1.38	0.09					
	Summer1989	1.64	0.18					
Návar and Bryan (1994)		13.52	2.95			4.5	Semi-arid vegetation	Mexico
Gash et al. (1995)		1.65	0.08	0.17	2.3	20.3	Plantation forest of maritime pine	France
Dykes (1997)		5.54	0.71	0.75		30–40	Lowland tropical forest	Burnei
Llorens (1997)		3.83	0.47			10	Pinus sylvestris	Spain
Valente et al. (1997)	Pinus	1.74		0.32	2.7	23.9	Pinus pinaster	Portugal
	Eucalyptus	1.81		0.20	3.2	16.5	Eucalyptus globulus	
Carlyle-Moses and Price (1999)	Pre-infestation	3.83	0.39	0.45		12–15	Temperate hardwood	Canada
	During infestation	12.98	1.29	1.53		12–15		
	Post infestation	3.36	0.15	0.18		12–15		
Schellekens et al. (1999)		1.85	0.94		5.9	20	Tabonuco type forest	Puerto Rico
Jackson (2000)		2.28		0.23		0.5–9.5	Agroforestry system	Kenya
Martin et al. (2000)	Sedimentary plain	5.88	0.342	0.411	4.4	25–30	Amazonian rain forest	Colombia
	High terrace	7.09	0.447	0.528	4.9	25–30		
	Low terrace	6.48	0.412	0.467	5.6	25–30		
	Flood plain	6.61	0.677	0.737	6.6	25–30		

van Dijk and Bruijnzeel (2001)	1995	4.7	0.86	1.178	2.0 (1.1–3.8)	<1.5	Maze, rice and cassava	Indonesia
	1999	4.3	0.30	0.545	1.3 (0.7–3.6)	<2.2		
Price and Carlyle-Moses (2003)		4.87	0.55	0.65		12–15	Mature mixed deciduous forest	Canada
		4.87	0.28	0.33		12–15		
Link et al. (2004)		0.78	0.14		8.60	60	Old-growth Doulas-fir-western hemlockecosystem	USA
Pyker et al. (2005)		1.33[a]	0.24[a]		10.20	20	Young Doulas fir	USA
Deguchi et al. (2006)	Entire study period	1.82	0.23	0.35	3.05	12	Decideous broad-leaves secondary forest	Japan
	Growing season	2.36	0.30	0.36	3.48	12		
	Dormant season	1.31	0.13	0.23	2.05	12		

[a] Calculated from Table 1 in Pyker et al. (2005).

Though scatter in the data is large, $\overline{E}$ shows an increasing trend for increasing $\overline{R}$, with a correlation coefficient of 0.589. The increasing trend of $\overline{E}_c$ with increasing $\overline{R}$ is clearer than that between $\overline{E}$ and $\overline{R}$, with a correlation coefficient of 0.810. These results again support the proposal that DOCI-ORI and SDE are a universal phenomenon that can be observed worldwide in the areas where rainfall intensity is high. One of the sources of scatter in the data is inconsistencies in the methods used to define rain events: methods vary from assuming a single storm per day (Gash, 1979) to defining an interval from the cessation of the rain event, whether it be 6 h (Murakami, 2006), 5 h (Deguchi et al., 2006) or 3 h (Schellekens et al., 1999). Other sources of scatter in the data are rainfall regime and hydrometeorological variability.

Vegetation height, LAI, and evaporation rate

One important aspect of Table 3 is the relation between $\overline{E}$ (or $\overline{E}_c$) and vegetation height. $\overline{E}$ or $\overline{E}_c$ does not depend on vegetation height: the correlation coefficient between $\overline{E}$ ($\overline{E}_c$) and vegetation height was 0.0332 (−0.0141). In Table 3, some vegetation heights are shown as a range of heights rather than fixed values. In such cases, the mean of the range in vegetation height was used to calculate the correlation coefficient. The exception to this approach is data from van Dijk and Bruijnzeel (2001); here, maximum heights were adopted as vegetation heights.

Generally, $\overline{E}$ or $\overline{E}_c$ highly depends on VPD and u, but if these variables are constant $\overline{E}$ or $\overline{E}_c$ is controlled by r_a. Although an assumption that VPD and u are constant does not hold true for the data in Table 3, an increase trend of $\overline{E}$ or $\overline{E}_c$ with decreasing r_a would be expected since the worldwide data in Table 3 could represent general trend. While the independence of $\overline{E}$ or $\overline{E}_c$ in terms of vegetation height means that values of r_a determined primarily from vegetation height (as described in Section ''Heat budget model'') are not a major parameter in terms of determining evaporation during rainfall. Eq. (10) and the relations $d = 0.78h$, and $z_0 = 0.07h$ imply that r_a decreases and that $\overline{E}$ or $\overline{E}_c$ increases with vegetation height; however, some values of $\overline{E}$ (or $\overline{E}_c$) in Table 3 are large for short vegetation. For very high $\overline{R}$ of 13.52 mm h^{-1}, Návar and Bryan (1994) obtained an $\overline{E}$ value of 2.95 mm h^{-1} for a vegetation height of only 4.5 m. van Dijk and Bruijnzeel (2001) demonstrated that $\overline{E}$ ($\overline{E}_c$) is 0.86 mm h^{-1} (1.178 mm h^{-1}) and 0.30 mm h^{-1} (0.545 mm h^{-1}) for low vegetation heights of <1.5 m and <2.2 m, respectively. These evaporation rates that are larger than or equivalent to those of the forest canopy cannot be attributed to vegetation height.

With respect to SDE it is assumed that the interception loss increases with tree height, since the fall distance is longer for taller trees, which gives splashed small droplets longer time to evaporate. In the present study canopy interception accounted for 19.1% of total rainfall in 1999 and 18.9% in 2000 for the tree height of 5.8 m and 6.3 m, respectively (Section ''Results''), while it does 14.8% in a stand of the same species with the tree height of 18 m in the same Watershed (Fig. 5a in Murakami et al., 2000). This result does not support the assumption; a small droplet with a radius of 25 μm evaporates and disappears with a fall of only less than 3 m (Fig. 4a in Murakami, 2006), and provided that slash droplet size distribution (SDSD) has a peak at less than 25 μm in radius SDE can be insensitive to the fall of over 3 m. At present SDSD is not available, which is a key to explore the details of the SDE.

The amount of splash droplet is affected by LAI, and this might influence $\overline{E}$ or $\overline{E}_c$. The relation between LAI and $\overline{E}$ or $\overline{E}_c$ was examined using the data in Tables 1 and 3 in terms of the correlation coefficient. Seasonal changes in LAI estimated in the present study were expressed as a function of DOY using 18 measurements of LAI undertaken in 2000. The value of the correlation coefficient between LAI and $\overline{E}$ or $\overline{E}_c$ are unexpectedly small: −0.0445 and 0.0265, respectively. This result means that both $\overline{E}$ and $\overline{E}_c$ are insensitive to LAI, in agreement with the findings of Deguchi et al. (2006) and Toba et al. (2006) who showed that canopy interception is insensitive to changes in LAI or PAI (see also Sections ''Introduction'' and ''Amount of splash droplet evaporation'').

Canopy interception is undoubtedly controlled by both meteorological factors including rainfall and forest structure; however, in terms of the evaporation rate during rain events that account for the greatest amount of canopy interception in many cases, climatic variability including rainfall intensity is a major governing factor whereas forest architecture is a minor factor.

Conclusions

To obtain a deeper understanding of DOCIORI and SDE, three canopy interception models, the heat budget, the DOCIORI, and the revised Gash models, were applied to a young stand of Japanese cypress for the years 1999 and 2000. The heat budget model underestimated observed interception by 62.9% in 1999 and 63.4% in 2000. The amount of underestimation is expected to be equal to the amount of SDE, as although canopy interception consists of SDE and evaporation from the canopy surface, the heat budget model calculates evaporation only from the canopy surface. The development and comparison of equations used in the DOCIORI and Gash models revealed that the DOCIORI and the Gash models are equivalent. DOCIORI was confirmed at interception sites in Spain (Llorens et al., 1997), Puerto Rico (Schellekens et al., 1999), and the USA (Link et al., 2004, Pyker et al., 2005) by reanalyzing the data from these earlier studies. The mean evaporation rate $\overline{E}$ or $\overline{E}_c$ and the mean rainfall intensity $\overline{R}$ calculated using Gash models were reviewed and analyzed along with data obtained in the present study. $\overline{E}$ or $\overline{E}_c$ demonstrated increasing trends with $\overline{R}$, which again supports the proposal that DOCIORI and SDE are universal phenomena. Literature data indicate that $\overline{E}$ or $\overline{E}_c$ are independent of tree height and LAI.

Acknowledgements

I wish to thank Yoshio Tsuboyama, Toshio Shimizu, Shoji Noguchi, Tayoko Kubota, and Motohisa Fujieda of the Forestry and Forest Products Research Institute for collecting data and maintaining instruments used in this study.

References

Calder, I.R., Wright, I.R., Murdiyarso, D., 1986. A study of evaporation from tropical rain forest-West Java. Journal of Hydrology 89, 13–31.

Carlyle-Moses, D.E., Price, A.G., 1999. An evaluation of the Gash interception model in a northern hardwood stand. Journal of Hydrology 214, 103–110.

Deguchi, A., Hattori, S., Park, H., 2006. The influence of seasonal changes in canopy structure on interception loss: application of the revised Gash model. Journal of Hydrology 319, 80–102.

Dolman, A.J., 1987. Summer and winter rainfall interception in an oak forest. Predictions with an analytical and a numerical simulation model. Journal of Hydrology 90, 1–9.

Dykes, A.P., 1997. Rainfall interception from lowland tropical rainforest in Brunei. Journal of Hydrology 200, 260–279.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quarterly Journal of the Royal Meteorological Society 105, 43–55.

Gash, J.H.C., Morton, A.J., 1978. An application of the Rutter model to the estimation of the interception loss from Thetford Forest. Journal of Hydrology 38, 49–58.

Gash, J.H.C., Wright, I.R., Lloyd, C.R., 1980. Comparative estimations of interception loss from three coniferous forests in Great Britain. Journal of Hydrology 48, 89–105.

Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology 170, 79–86.

Hattori, S., 1985. Explanation on derivation process of equations to estimate evapotranspiration and problems on the application to forest stand. Bulletin of the Forestry and Forest Products Research Institutes 332, 139–165 (in Japanese).

Hattori, S., Chikaarashi, H., 1988. Effect of thinning on canopy interception in a hinoki stand. Journal of the Japanese Forestry Society 70, 529–533 (in Japanese).

Hattori, S., Chhikaarashi, H., Takeuchi, N., 1982. Measurement of the rainfall interception and its micrometeorological analysis in a hinoki stand. Bulletin of the Forestry and Forest Products Research Institutes 318, 79–102 (in Japanese with English summary).

Herwitz, S.R., 1985. Interception storage capacities of tropical rainforest canopy trees. Journal of Hydrology 77, 237–252.

Hutjes, R.W.A., Wierda, A., Veen, A.W.L., 1990. Rainfall interception in the Tai forest, Ivory Coast: application of two simulation models to a humid tropical system. Journal of Hydrology 114, 259–275.

Iida, S., Tanaka, T., Sugita, M., 2005. Change of interception process due to the succession from Japanese red pine to evergreen oak. Journal of Hydrology 315, 154–166.

Jackson, N.A., 2000. Measured and modelled rainfall interception loss from an agroforestry system in Kenya. Agricultural and Forest Meteorology 100, 323–336.

Kondo, J., Nakamura, T., Yamazaki, T., 1991. Estimation of the solar and downward atmospheric radiation. Tenki (the Bulletin Journal of the Meteorological Society of Japan) 38, 41–48 (in Japanese).

Kondo, J., Watanabe, T., Nakazono, M., Ishii, M., 1992. Estimation of forest rainfall interception. Tenki (the Bulletin Journal of the Meteorological Society of Japan) 39, 159–167 (in Japanese).

Leyton, L., Reynolds, E.R.C., Thompson, F.B., 1967. Rainfall interception in forest and moorland. In: Sopper, W.E., Lull, H.W. (Eds.), International Symposium on Forest Hydrology. Pergamon Press, Oxford, pp. 63–178.

Link, T.E., Unsworth, M., Marks, D., 2004. The dynamics of rainfall interception by a seasonal temperate rainforest. Agricultural and Forest Meteorology 124, 171–191.

Llorens, P., 1997. Rainfall interception by a *Pinus sylvestris* forest patch overgrown in Mediterranean mountainous abandoned area II. Assessment of the applicability of Gash's analytical model. Journal of Hydrology 199, 346–359.

Llorens, P., Poch, R., Latron, J., Gallart, F., 1997. Rainfall interception by a *Pinus sylvestris* forest patch overgrown in Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. Journal of Hydrology 199, 331–345.

Lloyd, C.R., Gash, J.H.C., Shuttleworth, W.J., 1988. The measurement and modelling of rainfall interception by Amazonian rain forest. Agricultural and Forest Meteorology 43, 277–294.

Loustau, D., Berbigier, P., Granier, A., 1992. Interception loss, throughfall and stemflow in a maritime pine stand. II. An application of Gash's analytical model of interception. Journal of Hydrology 138, 469–485.

Marshall, J.S., Palmer, W.M., 1948. The distribution of raindrops with size. Journal of Meteorology 5, 165–166.

Martin, C.T., Bouten, W., Sevink, J., 2000. Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystem in western Amazonia. Journal of Hydrology 237, 40–57.

Monteith, J.L., 1965. Evaporation and the environment. Symposium of the Society of Experimental Biology 19, 245–269.

Murakami, S., 2006. A proposal for a new forest canopy interception mechanism: splash droplet evaporation. Journal of Hydrology 319, 72–82.

Murakami, S., 2007. Analysis of canopy interception in a Japanese cypress stand using Gash models. Transactions of Kanto Branch of the Japanese Forest Society 58, 149–151 (in Japanese).

Murakami, S., Tsuboyama, Y., Shimizu, T., Fujieda, M., Noguchi, S., 2000. Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment. Journal of Hydrology 227, 114–127.

Návar, J., Bryan, R.B., 1994. Fitting the analytical model of rainfall interception of Gash model to individual shrubs of semi-arid vegetation in northern México. Agricultural and Forest Meteorology 68, 133–143.

Pearce, A.J., Gash, J.H.C., Stewart, J.B., 1980. Rainfall interception in a forest stand estimated from grassland meteorological data. Journal of Hydrology 46, 147–163.

Price, A.G., Carlyle-Moses, D.E., 2003. Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. Agricultural and Forest Meteorology 119, 69–85.

Pyker, T.G., Bond, B.J., Link, T.E., Marks, D., Unsworth, M.H., 2005. The importance of canopy structure in controlling the interception loss of rainfall: examples from a young and an old-growth Douglas-fir forest. Agricultural and Forest Meteorology 130, 113–129.

Row, L.K., 1983. Rainfall interception by an evergreen beech forest, Nelson, New Zealand. Journal of Hydrology 66, 143–158.

Rutter, A.J., Kershaw, K.A., Robins, P.C., Morton, A.J., 1971. A predictive model of rainfall interception in forests I. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9, 367–384.

Rutter, A.J., Morton, A.J., Robins, P.C., 1975. A predictive model of rainfall interception in forests II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. Journal of Applied Ecology 12, 367–380.

Schellekens, J., Scatena, F.N., Bruijnzeel, L.A., Wickel, A.J., 1999. Modelling rainfall interception by a lowland tropical rain forest in northern Puerto Rico. Journal of Hydrology 225, 168–184.

Toba, T., Ohta, T., Shiraki, K., Enatsu, T., 2006. Characteristics of rainfall interception loss using tree models: consideration of the interception loss in rainfall. The Japanese Forest Society Congress 117, 459 http://www.jstage.jst.go. jp/article/jfsc/117/0/117_459/_article (in Japanese).

Tsukamoto, Y., Tange, I., Minemura, T., 1988. Interception loss from forest canopies. Hakyuchi-kenkyu (Bulletin of the Institute for Agricultural Research on Rolling Land) 6, 60–82 (in Japanese with English summary).

Valente, F., David, J.S., Gash, J.H.C., 1997. Modelling interception loss for two sparse eucalypt and pine forest in central Portugal using reformulated Rutter and Gash analytical models. Journal of Hydrology 190, 141–162.

van Dijk, A.I.J.M., Bruijnzeel, L.A., 2001. Modelling rainfall interception by vegetation of variable density using an analytical model. Part 2. Modelling validation for a tropical upland mixed cropping system. Journal of Hydrology 247, 239–262.