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A proposal for a new forest canopy interception mechanism: Splash droplet evaporation

Shigeki Murakami*

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

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Abstract

Canopy interception was observed at a young stand of *Chamaecyparis obtusa* in a small Japanese experimental watershed for 2 years. Hourly canopy interception is linearly related to hourly rainfall on a rain event basis; this implies a dependence of the canopy interception on the rainfall intensity (*DOCIORI*). The *DOCIORI* became stronger from spring to summer and declined from fall to winter. Though canopy interception has been treated as evaporation from wet canopy surfaces, this concept cannot be accountable for (1) the *DOCIORI* and (2) the efficient canopy interception mechanism, as about 10–40% of the rainfall evaporates during rain events under high humidity conditions. A new concept is proposed to explain these contradictions: numerous small droplets are produced by splashes when a raindrop hits a canopy and they evaporate. It is well known that the specific number and the average size of raindrops increases with rainfall intensity, and, as a result, so do the number of small droplets produced by splashes and evaporation. This splash mechanism can explain both the *DOCIORI* and the efficient canopy interception mechanism based on simulations. A droplet of 25 μm in radius falling at its terminal velocity under a relative humidity of 95% evaporates and disappears after 1.7–2.8 m of fall distance, depending on the ambient temperature (15–25 °C), while one of 50 μm loses 20–32% of its original mass after 8 m of fall distance. However, a droplet of 100 μm in radius loses only 2–4% of its original mass with an 8 m fall distance. Seasonal changes in the *DOCIORI* are also partly explainable by the splash mechanism.

Keywords: Canopy interception; Rainfall intensity; Splash; Droplet

1. Introduction

Evaporation by forest canopy interception accounts for about 10–40% of the total rainfall (Hörman et al., 1996) and affects water and geochemical balances in forest areas. Therefore, the modeling of canopy interception has significant implications from the local to the global scale, i.e. from forest watershed management (Calder, 1990) to atmospheric general circulation models (GCMs) (Dolman and Gregory, 1992). So far, forest canopy interception has been treated as evaporation from wet canopy surfaces. A heat budget model (Rutter et al., 1971; 1975) takes this concept into account and is

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

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widely used. Nevertheless, this approach includes at least two contradictions.

Firstly, though it is pointed out that interception is driven mainly not by radiation but by sensible heat (Stewart, 1977; Sing and Szeicz, 1977; Peace et al., 1980; Kelliher et al., 1992; Asdak et al., 1998), there is no explanation for the mechanism of the efficient evaporation of the intercepted water under high humidity conditions during a rain event. Even if predictions made with a heat budget method, like the Penman–Monteith (P–M) equation, agree well with measurements, it is a natural result and does not mean that you have explained the mechanism of canopy interception. The parameters in the equation have been determined so that they fit with the measured values, even if the measurement to determine the parameters is independent from the measurement that you want to predict. This 'tuning' of the parameters fits predictions to the measurements. As a result heat budget is consistent and the parameters are known, but the mechanism is still unveiled. The crux of the matter is to know why the parameters, the aerodynamic resistance in case of the P–M equation, take that value, which enable high evaporation rate of intercepted rainfall.

Secondly, there are some papers that indicate a dependence of the canopy interception on the rainfall intensity (*DOCIORI*) (Hattori et al., 1982; Tsukamoto et al., 1988; Jackson, 2000), but no conventional heat budget models can explain this phenomenon because they do not include any parameters related to the rainfall intensity. A series of studies (Calder, 1996; Calder et al., 1996; Hall et al., 1996; Hall, 2003) investigated dependence of rainfall interception on raindrop size and rainfall intensity, but all of them focused on the relation between raindrop size, rainfall intensity and water storage on canopy to test the stochastic model (Calder, 1986; Hall, 1992). The stochastic model requires the P–M equation, one kind of heat budget methods, however, the effect of raindrop size and rainfall intensity is not included in the P–M equation but in the wetting functions of the model. Therefore, the *DOCIORI* is not considered in terms of heat budget.

Yulianur et al. (1998) developed a tank-type interception model in which they take the rainfall intensity into consideration as a parameter to account for the *DOCIORI*. By doing this they improved the accuracy of monthly interception estimates. As a mechanism of the *DOCIORI*, Yulianur et al. (1998) assumed that splash droplets produced on a canopy float above the canopy and that the droplets do not evaporate, though they showed no evidence of this mechanism. At present, there are no clues to account for this phenomenon.

In this study, canopy interception in a young stand of *Chamaecyparis obtusa* in a Japanese small forest watershed has been observed in order to analyze the *DOCIORI* (Murakami, 2004). To explain the *DOCIORI*, a hypothesis is introduced, called the canopy interception mechanism, or splash droplet evaporation, which can explain both of the contradictions: the *DOCIORI* and the mechanism of the efficient evaporation of the intercepted water. The validity of this hypothesis was evaluated by the simulation of droplet evaporation under high humidity conditions which is equivalent conditions prevailing during rain event.

2. Hypothesis of splash droplet evaporation

When a raindrop hits a canopy, it splashes and numerous small droplets are produced. The number of small droplets produced by this process increases with rainfall intensity, because the specific number and average size of the raindrops increase with rainfall intensity (Marshall and Palmer, 1948; Willis and Tattleman, 1989) that enhance the kinetic energy of the incident raindrops.

Therefore, if only small droplets evaporate efficiently during a rain event, both contradictions mentioned in the previous chapter can be explained. Firstly, the efficient evaporation during rain events can be explained because evaporation occurs not only on the canopy surface but also on the small droplet surfaces during their fall towards the ground in air. Generally speaking turbulence exists and droplets are affected, however, they fall towards the ground in the long run. Secondly, the *DOCIORI* is apparent since with increasing rainfall intensity, more small droplets are produced.

Though the splash process has been studied in terms of the dispersal of plant pathogens (Yang et al., 1991; Huber et al., 1997; Saint-Jean et al., 2004), Saint-Jean et al. (2004) pointed out that splash droplet generation is a complex process that cannot yet be precisely predicted theoretically. In these studies, the evaporation of splash droplets was not considered. So far, there are insufficient data to discuss both small droplet production and their evaporation after the splash.

The *DOCIORI* was observed and the evaporation rate of a small droplet under high humidity conditions was simulated to evaluate this hypothesis. The results are presented in the following chapters.

3. Method

3.1. Site and observations

Canopy interception was measured in a *C. obtusa* stand planted in 1988 at the Hitachi Ohta Experimental Watershed on the Pacific coast of eastern Japan at an altitude of 320 m (Fig. 1, Murakami et al., 2000), which consists of some sub-catchments. Runoff and meteorological observations are also conducted in this Watershed. Monthly precipitation is shown in Table 1. Precipitation in the winter is small and most of the rain events occur during the other seasons.

The stand density of *C. obtusa* was 2944 trees/ha with an average tree height of 5.8 m in May 1999 and 6.3 m in October 2000, respectively. The leaf area index (LAI) measured by an LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE, USA) in 2000 changed from 3.9 to 5.2 with season (Murakami, 2002) and the canopy was almost closed. The gross rainfall, throughfall and stemflow were measured by the same method with Murakami et al. (2000) during the years 1999–2000. The throughfall was measured using two troughs, 590 cm long and 18 cm wide, and stemflow gauges were set on eight trees. Stemflow and throughfall were collected in a tank, respectively, and each water level was recorded on the chart paper. The recorded water level was then converted to water depth. Two raingauges were installed at the Watershed and the values at the two sites were averaged. The canopy interception was derived as the difference between the gross precipitation and

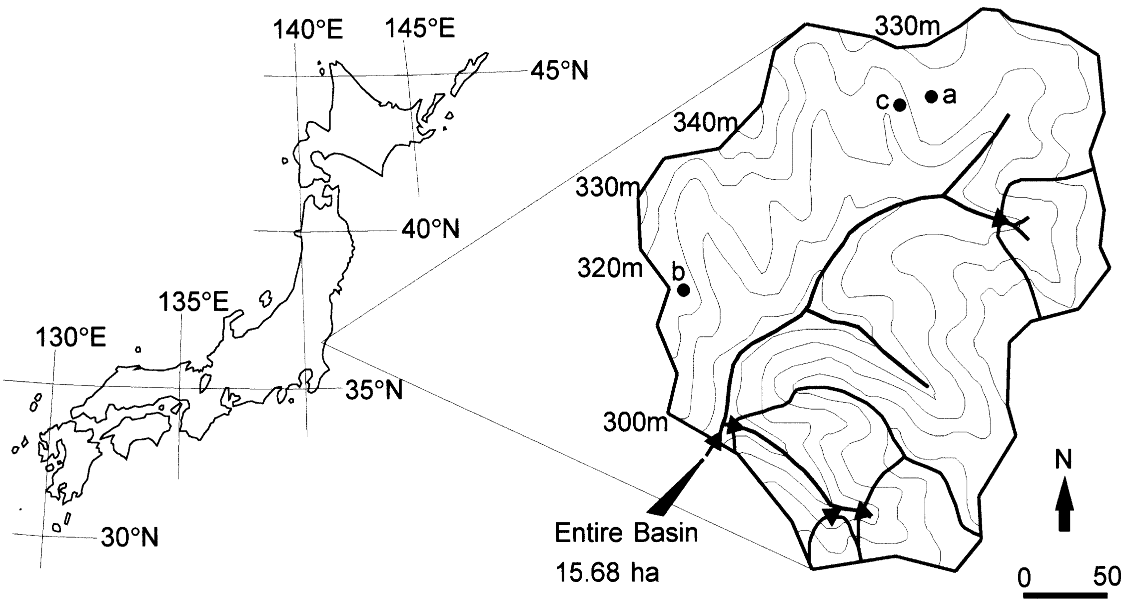

Fig. 1. Hitachi Ohta Experimental Watershed. (a) Meteorological station with a raingauge, (b) raingauge, (c) canopy interception plot, (▲) gauging weir.

Table 1
Monthly precipitation in the Hitachi Ohta Experimental Watershed

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1999	2.0	41.5	135.5	304.5	203.0	250.9	276.0	135.2	100.8	173.6	67.6	17.3	1707.9
2000	71.6	19.3	74.8	186.5	181.8	187.7	249.1	45.7	226.2	125.5	77.9	6.8	1452.9
Average 1991–2000	51.6	49.6	112.5	127.6	186.3	165.6	164.7	127.5	219.7	135.4	94.5	32.7	1467.7

Units are millimeters.

the net precipitation (summation of the throughfall and stemflow). The annual canopy interception in 1999 was 335.5 mm (interception rate: 19.6%), while in 2000 it was 262.6 mm (interception rate: 18.1%). Snow accounted for 34.3 and 21.3 mm of the annual precipitation in 1999 and 2000, respectively, and thus was a minor component of the precipitation.

Though canopy interception has been analyzed on a daily or a rain event basis in most studies, in the present study, it was done on an hourly basis for each rain event. Rain events were delimited when no rainfall was observed for more than 6 h since the cessation of rainfall from the previous event.

Rain events considered were those with total accumulations of more than or equal to 20 mm. This was done for two reasons. One is that since hourly analysis is conducted, the rainfall duration for a certain rain event must cover at least several hours to obtain enough samples. A rain event with a total rainfall of 20 mm or more usually has duration of several hours, except for under thunderstorm conditions: such local thunderstorms were excluded. Another is that the result is discussed in connection with humidity data which are measured at the Mito Meteorological Observatory (25 km southwest of Hitachi Ohta): humidity was measured at the site. However, the measurable range of a high polymer hygrometer is less than 95% and humidity cannot be measured during a rain event. Typical rain events, here assumed to be those over 20 mm, are brought by depressions, typhoons or fronts whose scales are sufficiently large in comparison with the distance between Hitachi Ohta and Mito. Therefore, the humidity difference between the two sites is not significant in most cases. In addition to this, such rain events occur both at Hitachi Ohta and Mito at the same time. Therefore, it is reasonable to assume that humidity data measured at Mito is representative of that at Hitachi Ohta.

3.2. Simulation of droplets evaporation

The mass reduction of a small droplet due to evaporation falling at the terminal velocity was estimated as a function of the fall distance. The evaporation of a droplet, a function of the ambient relative humidity (*RH*), temperature and droplet radius, was calculated based on Beard and Pruppacher (1971). The velocity of a droplet is a function of the droplet radius that varies with time due to evaporation. By iterating the radius changes by evaporation and the fall distance estimated by the equations described below, it is possible to express the mass reduction of a small droplet with fall distance.

The equation of motion for a droplet is given by

$$m\frac{dv}{dt} = mg - mg\frac{\rho_f}{\rho_p} - R_f \tag{1}$$

where m, v, ρ_p, R_f, g, and ρ_f are the mass, velocity, density, the drag force of the droplet, the gravitational acceleration and the density of air, respectively. The first and the second term on the right-side of Eq. (1) represent the gravitational force and the buoyant force, respectively. Assuming that the droplet is a sphere, the drag force R_f can be defined as

$$R_f = C_R\left(\frac{\rho_f v^2}{2}\right)\pi r^2 \tag{2}$$

where C_R (dimensionless) is the drag coefficient for a sphere with a radius of r which is a function of Reynolds number as described later. Using the relationship $m = 4/3\pi r^3 \rho_p$ and Eq. (2), Eq. (1) can be written as

$$\frac{dv}{dt} = g\left(\frac{\rho_p - \rho_f}{\rho_p}\right) - \left(\frac{3\rho_f}{8\rho_p r}\right)C_R v^2 \tag{3}$$

At the terminal velocity v_t, the left-side of Eq. (3) is equal to zero, therefore:

$$v_t = \left(\frac{8gr(\rho_p - \rho_f)}{3\rho_f C_R}\right)^{1/2} \tag{4}$$

The drag coefficient C_R changes depending on the Reynolds number (dimensionless), $Re(=2r\rho v/\mu)$, where μ is the dynamic viscosity of the fluid

$$C_R = \frac{24}{Re} \quad \text{for } Re < 0.1 \tag{5}$$

$$C_R = \left(0.5407 + \sqrt{\frac{24}{Re}}\right)^2 \tag{6}$$

for $0.1 \leq Re \leq 6000$

Eq. (5) is the law of Stokes and Eq. (6) is described in Bird et al. (2002). You can obtain the relationship between the mass reduction of a droplet and the fall distance by combining Eqs. (4)–(6), and estimating the droplet radius which changes with time because of evaporation (Beard and Pruppacher, 1971).

4. Results

4.1. Observation of canopy interception

The canopy interception was analyzed for 38 rain events for the years 1999–2000 that had over or equal to 20 mm of rainfall. Fig. 2(a)–(f) shows examples of the analysis. The hourly canopy interception shows a linear relationship with hourly rainfall in each rain event. The inclination of the regression line i, which implies the *DOCIORI*, varied with season. From spring to summer the value of i rises with time, while from summer to autumn it diminishes. The increase and the decrease trend in slopes in Fig. 2 are statistically significant. The seasonal changes in i for 2 years clarify this trend, as shown in Fig. 3(a).

4.2. Simulation of droplet evaporation

The *RH* of the ambient air is fixed at 95%. This value is nearly equal to the average actual *RH* of 94% (a standard deviation of 1.9) during the rain events at the Mito Meteorological Observatory for the years 1999–2000 when rainfall accumulations of 20 mm or more were observed in Hitachi Ohta. Three air temperatures, 10, 15, and 25 °C, and radii 25, 50, and 100 μm, were used for the simulation.

A droplet of 25 μm in radius evaporates and disappears with a fall distance of 2.8 m at 10 °C, 2.4 m at 15 °C, and 1.7 m at 25 °C and takes 73, 61, and 47 s to disappear, respectively (Fig. 4(a)). A droplet of radius 50 μm loses 20% of its original mass at 10 °C, 24% at 15 °C, and 32% at 25 °C with a fall distance of 8 m and it takes 36, 37, and 38 s, respectively (Fig. 4(b)). However, a droplet 100 μm in radius hardly evaporates, as it reduces by 2% of its original mass at 10 °C, 3% at 15 °C, and 4% at 25 °C, during a fall distance of 8 m taking 12 s at any of these three temperatures (Fig. 4(c)).

This kind of studies has been conducted by cloud physicists based on measurement, experiment, and theory. You have to note when a radius of a

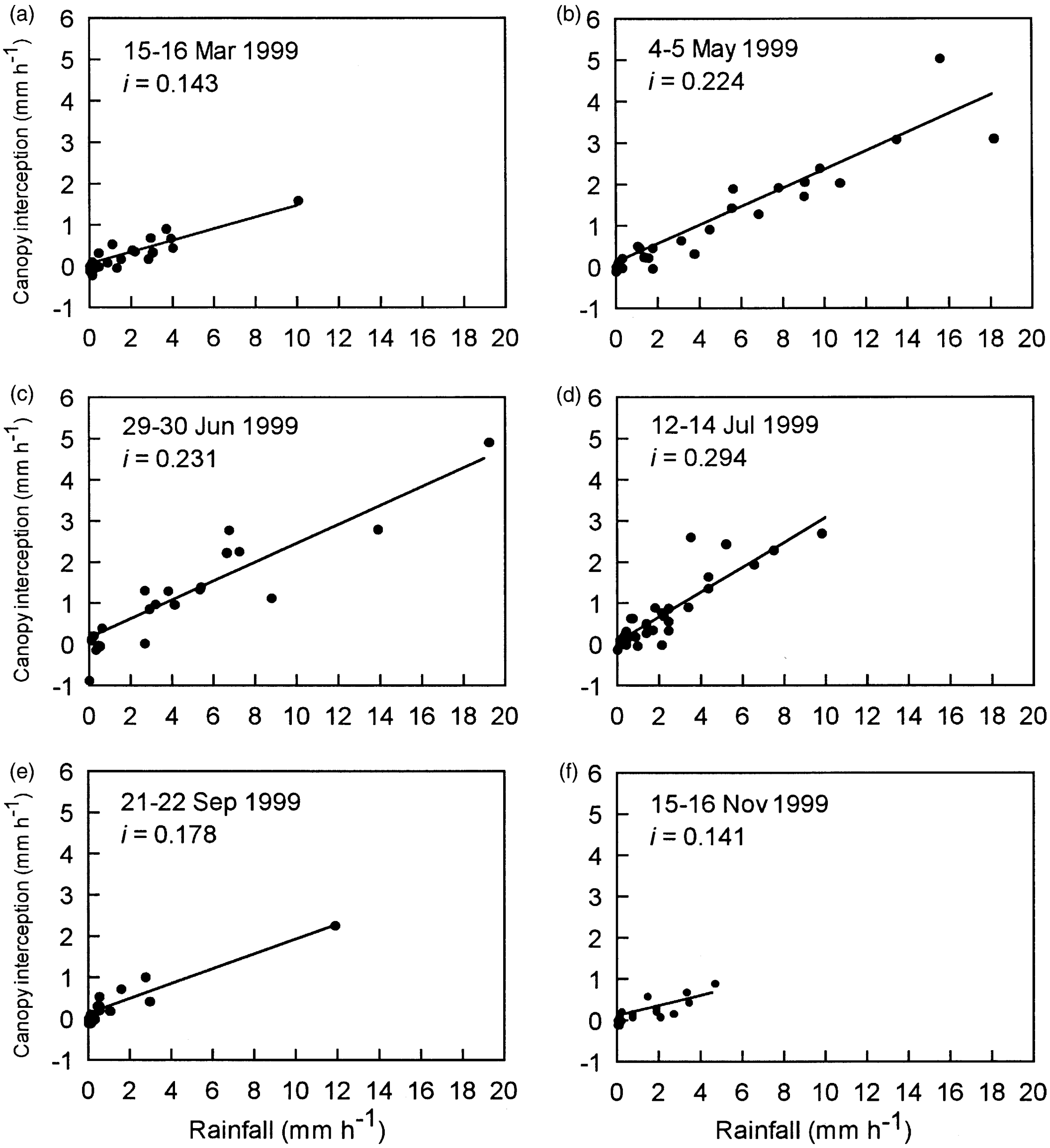

Fig. 2. Examples of the dependence of canopy interception on rainfall intensity (*DOCIORI*). Each panel represents an analysis of one rain event. Total rainfall of each panel: (a) 40.2 mm, (b) 132.6 mm, (c) 94.3 mm, (d) 72.3 mm, (e) 22.5 mm, and (f) 24.2 mm. Some of the measured canopy interceptions are negative due to observational errors. The solid lines are calculated regression lines, except those with negative values. The inclination of the regression line, *i*, is indicated in each panel.

droplet is small; saturated water vapour pressure for the small droplet is significantly higher than that of flat water surface. Assuming that water vapour pressure for flat water surface is 100 (arbitrary unit), then, saturated water vapour pressure for the droplet with radius of 10, 1, 0.1, and 0.01 μm are 100.01, 100.12, 101.2, and 112.5, respectively. To keep equilibrium of the small droplet, large supersaturation is required or it would disappear due to evaporation. This implies that under supersaturated condition larger droplets grow at the expense of smaller ones. In this study, simulated minimum

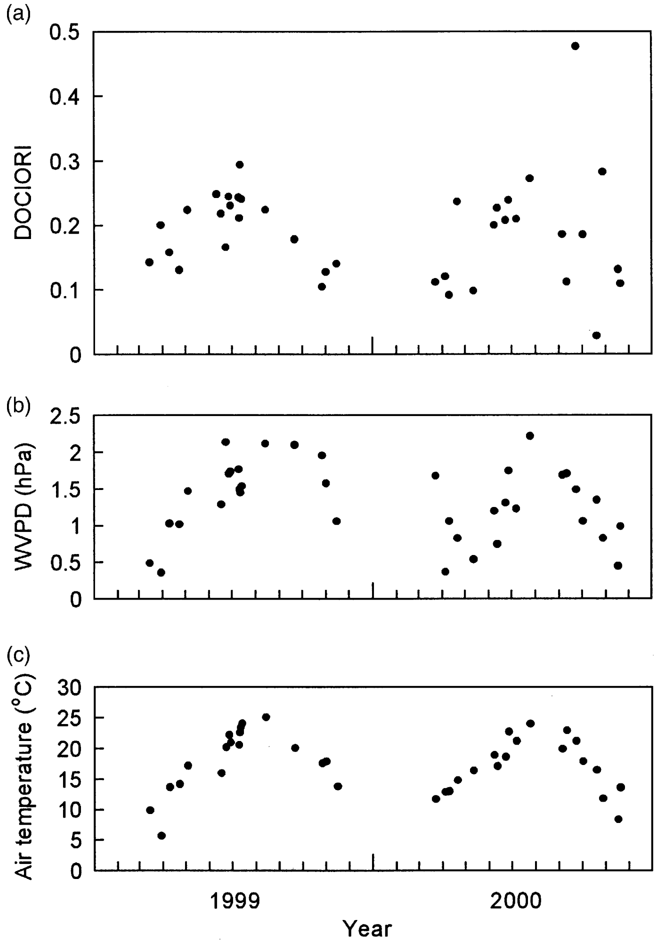

Fig. 3. (a) Seasonal changes in the dependence of the canopy interception on the rainfall intensity (*DOCIORI*), *i*, at Hitachi Ohta. (b) Seasonal changes in the water vapour pressure deficit (*WVPD*) during rainfall at the Mito Meteorological Observatory, 25 km southwest of Hitachi Ohta. (c) Air temperature under the same condition with (b). The values of *WVPD* (b) and air temperature (c) corresponding to the rain event in the panel (a) are shown.

droplet radius was 25 μm and there was no need to take this radius effect into consideration.

5. Discussion

5.1. Mechanism of DOCIORI

Canopy interception consists of three processes: firstly, rainwater used to wet the canopy surface mainly occurs at the beginning of a rain event; secondly, evaporation from the canopy surface; and thirdly, evaporation from splash droplets. Assuming that little evaporation occurs, the canopy saturates when the rainfall amount reaches the storage capacity of the canopy. The storage capacity at the *C. obtusa* stand in Hitachi Ohta was 0.5 mm in 1999 and 0.7 mm in 2000, based on observations. These values are small in comparison with the total canopy interception for each rain event in this study, because rain events of over 20 mm were considered. Therefore, water storage on the canopy does not affect the trend for hourly canopy interception analysis (Figs. 2 and 3(a)).

The main components of canopy interception are the evaporation from the canopy surface and from the splash droplets. Here, the latter is proposed, which

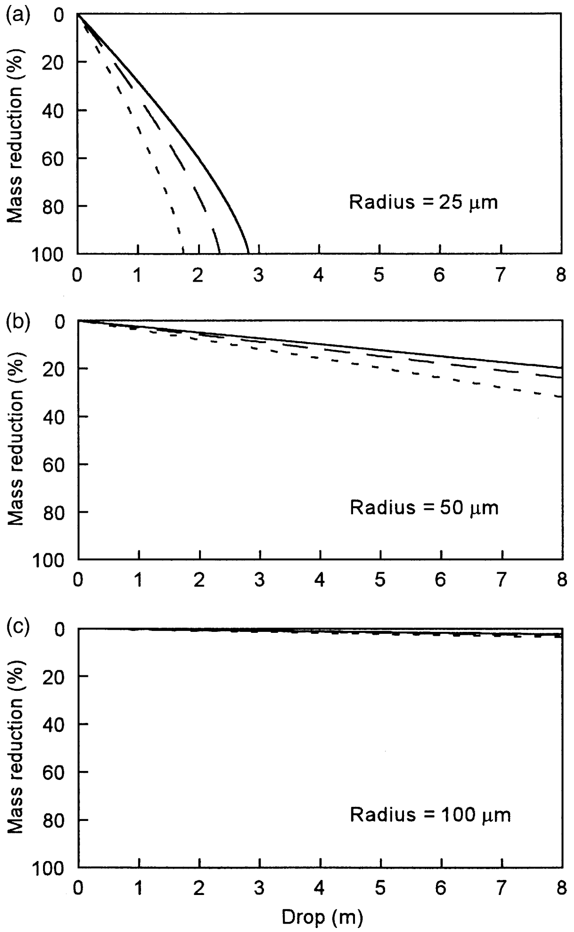

Fig. 4. Mass reductions of small droplets falling at the terminal velocities with fall distance. Three ambient temperatures are assumed: 10 °C (dotted line), 15 °C (broken line) and 25 °C (solid line). The relative humidity (*RH*) was set at 95%. (a) 25 μm in radius, (b) 50 μm, and (c) 100 μm.

depends on the rainfall intensity, while the Rutter model (Rutter et al., 1971) assumes that the former also depends on the rainfall intensity at the initial stage of the rainfall. However, in the Rutter model, once the water on the canopy reaches the storage capacity, evaporation of canopy interception is not affected by the rainfall intensity. Among the three canopy interception processes, the only process that can explain the *DOCIORI* is splash droplet evaporation.

Fig. 4(a)–(c) demonstrated that small droplets can evaporate under high humidity conditions during rain events. That is, this result supports the hypothesis mentioned in the second chapter and explains both contradictions mentioned in the first chapter: the efficient interception mechanism and the *DOCIORI*. However, it is not known to what extent droplet evaporation contributes to canopy interception due to the lack of splash droplet size distribution (*SDSD*) data.

5.2. Seasonal changes in DOCIORI

Seasonal changes in the *DOCIORI* (Figs. 2(a)–(f) and 3(a)) can be partly interpreted by the splash mechanism. Among the meteorological elements in the ambient air of a droplet, the main variable that controls the seasonal variation in the *DOCIORI* is the water vapour pressure deficit (*WVPD*). The following elements are excluded as determinant factors: wind speed, *RH*, and net radiation. The wind speed is excluded since a small droplet falls at the terminal velocity, which is regarded as the wind speed for the small droplet. The *RH* and the net radiation are also excluded, because evaporation occurs under an almost constant *RH* of 94% (as mentioned in Section 4.2) and the net radiation during a rain event is small.

Assuming constant *RH*, *WVPD* is governed by the air temperature, because *WVPD* is related to *RH* through the following equation

$$WVPD = \left(1 - \frac{RH}{100}\right) e_{\text{sat}} \tag{7}$$

where e_{sat} is saturated water vapour pressure that is approximately regarded as a function of temperature. Under constant *RH*, the small droplet evaporation is also governed only by air temperature, assuming that the *SDSD* is controlled only by the rainfall intensity throughout the year. Actually, seasonal changes in the *DOCIORI* (Fig. 3(a)) demonstrate similar patterns with *WVPD* and air temperature during rainfall (Fig. 3(b) and (c)). Air temperatures during rainfall vary roughly between 10 and 25 °C with seasons (Fig. 3(c)). This temperature difference changes the evaporation rate of small droplets by about 40% (Fig. 4). However, seasonal changes in the *DOCIORI* vary from some 0.1 to 0.25 (Fig. 3(a)), which is a variation of 250%. That is, temperature differences can partly explain the seasonal changes in the

DOCIORI in terms of *WVPD*. The major mechanism of seasonal changes in the *DOCIORI* remains unaccountable, but at least the following two factors have to be taken into consideration.

Firstly, seasonal changes in the forest structure may influence the production rate of small droplets. Even at an evergreen coniferous stand, LAI varied between 4 and 5 annually (Murakami, 2002), and this may reduce the winter interception. Secondly, the raindrop size distribution (*DSD*) depends on the cloud type (Tokay and Short, 1996), season and/or location (Kozu et al., 2002): differences in the *DSD* directly affect the production rate of splash droplets and the total evaporation of the intercepted water.

Gash (1979) showed that mean evaporation rate has a maximum in summer (in his Fig. 1) and this is the same trend with this study, though he did not mention it. Gash (1979) also said there is no significant correlation between mean evaporation rate and mean rainfall intensity that does not support this study. However, this is because Gash analysed 4-week period basis, which is probably too long to reveal the relation.

5.3. For future study

What is needed in order to prove the splash evaporation hypothesis directly is to measure the *SDSD*. A laser particle counter is a useful tool for measuring the size of small particles but the area of the laser beam is too narrow for measuring the *SDSD*. Therefore, this approach is not practical. An experimental study that confirms the *DOCIORI*, based on the water balance method, is one possible approach, though it would provide indirect proof and as such is a useful check for this study. Changing the raindrop size and/or the velocity is easy, and extensive experiments can be made.

Huber et al. (1997) showed that the efficiency of a splash depends on both the target conditions and the raindrop size. They indicated that more water was splashed from oilseed rape leaves that have a waxy smooth surface than from tobacco leaves that have a hairy surface. The effect of target angle was greater for large drops and the greatest amount of water was splashed from horizontal targets. They also revealed that the relationship between drop diameter and the mass of water splashed could be described by a power law. As for forest canopy interception, the target characteristics consisting of the tree architecture, the angle of leaf surfaces, and the surface state of leaves are much more complex than those of the agricultural plants studied by Huber et al. (1997), because the LAI and biomass in forests are significantly larger and the surface state of the leaves are more variable, even within an individual, than in agricultural plants. A combination of a Huber-type experiment and the water balance method must be efficient for future studies.

In this study, energy and water vapour transport are not discussed, because it is much more enigmatic than evaporation of intercepted rainfall. The followings are the possible self-consistent mechanism for them. As mentioned in chapter 1, evaporation of intercepted rainfall is mainly driven by sensible heat. Consumption of sensible heat reduces air temperature and this leads to the reduction in *WVPD* and evaporation rate. Thus, energy must be supplied to compensate for this. Evaporation occurs in the canopy, on the contrary, condensation occurs in the cloud. The former consumes latent heat but the latter releases it and those two can balance. At the same time water vapour that evaporated in the canopy should be removed otherwise *WVPD* and evaporation rate decreases again. Water vapour can go up to the air and condense at the condensation level releasing latent heat. The mechanism of energy and water vapour transport is unknown, but evaporation of canopy interception cannot be maintained without such a circulation.

6. Conclusions

At present, there are two contradictions in the study of canopy interception. Firstly, though the evaporation of canopy interception accounts for some 10–40% of the rainfall, there are no reasonable explanations for the mechanism of efficient evaporation under high humidity conditions. Even if heat budget is consistent and the amount of evaporation of canopy interception is predictable by a heat budget model, it does not mean that you have explained the mechanism of high evaporation rate of canopy interception. The parameters in the heat budget model are determined so that they fit with the measured values. If the measurement to determine the parameters is independent from the measurement that you want to predict, it is of no importance; the mechanism is still in the black box. Secondly, some forest hydrologists have reported that canopy interception depends on the rainfall intensity, but this cannot be explained by the conventional heat budget models. Here, a new concept has been proposed to account for those two contradictions: a raindrop which hits the canopy splashes, and small droplets are produced that evaporate during their fall toward the ground. This hypothesis, called the splash evaporation mechanism, can explain both of the contradictions mentioned above. Firstly, the huge surface area of small droplets enables an efficient evaporation of water. Secondly, the *DOCIORI* is also explainable by this hypothesis because the number of raindrops per unit volume and the raindrop size increase with rainfall intensity, which enhances the number of splash droplets produced.

To evaluate this hypothesis, observations of canopy interception at a stand of *C. obtusa* and simulations of small droplet evaporation were conducted. Observations revealed a *DOCIORI* and its seasonal changes that were stronger in summer than in winter. Simulations demonstrated that a droplet of several decades of micrometers in radius had a sufficiently high evaporation rate, which explains the hypothesis, even under high humidity, and that seasonal changes in the *DOCIORI* can be partly accountable by changes in seasonal temperatures.

In addition to evaporation from a wet canopy surface, evaporation from small droplets produced by raindrop splashes has to be considered and taken in account in canopy interception models.

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