# Chapter 4

# Influence of canopy species and meteorological factors for throughfall drop generation: A field observation of throughfall under three canopy species

## 4.1 Introduction

**Interception process in canopies**: The interception of precipitation by vegetation canopies is a major component of the surface water balance in watersheds. Many interception studies have been conducted worldwide by both observational and modeling methods (summarized in Link et al., 2004). Among interception process models (Rutter et al., 1971; Gash, 1979), a two-layer stochastic model (Calder, 1996; Calder et al., 1996) accounts for the gradual wetting of a vegetation canopy by raindrops and water then dripping from an upper canopy layer onto a lower one. The interception losses were dependent not only upon the intensity of rainfall events (Crockford and Richardson, 2000; Murakami, 2006) but also upon the size of the drops (Calder, 1996), and differences in interception losses among canopy species were explained by the size of throughfall drops (Hall, 2003). Evaluating the drop size distribution (DSD) of throughfall is necessary for input into stochastic models in order to better understand the interception process.

**Causes of throughfall-DSD variation:** It was previously thought that throughfall-DSD was independent of canopy species (Vis, 1986; Brandt, 1989) and rainfall intensity (Chapman, 1948; Mosley, 1982; Vis, 1986), employing manual drop sizing techniques such as the use of filter paper or flour pellet methods. A two-level stochastic model has been used on the assumption that throughfall-DSD was constant within each rainfall event (Hall, 2003). However, automatic drop sizing techniques have provided different results. Hall and Calder (1993) showed that throughfall-DSD varied among canopy species in tropical regions. In *'Chapter 3'*, the throughfall-DSD varied between rainfall events and also within events; I hypothesized that severe wind vibration within the canopy caused the drops of water dripping from the canopy to become small. Vibration of the canopy is caused by wind and/or raindrop impact onto the canopy; hence, it would be expected that throughfall-DSD would fluctuate in response to the temporal variations of meteorological factors as well as to differences in canopy species. A detailed study was needed to clarify the characteristics of throughfall-DSD variations for use in process studies on intercepted rainfall.

**Objectives of this study**: The objective of this study was to evaluate the influence of canopy species and meteorological factors on throughfall-DSD variations. Simultaneous measurements of raindrops were continuously performed in three forest stands with different canopy species, and also at an open site. I estimated the characteristics of canopy species on throughfall-DSD based on comparisons of drop size data among different canopy species under the same meteorological conditions. Similarly, I estimated the same parameter under varying meteorological conditions.

## 4.2 Materials and methods

*Site description*

Observations were conducted at the Tanashi Experiment Station of the University of Tokyo, Tokyo, Japan (Fig. 4.1). The station is located at 35°44'N, 139°32'E on a flat area at 60 m elevation. The station contains model forests and arboreta with about 350 species within 9.1 ha. The mean annual precipitation is 1350 mm and the mean annual temperature is 15.5°C, 1971–2000. I established an open rainfall observation site and three throughfall observation sites under stands of three different

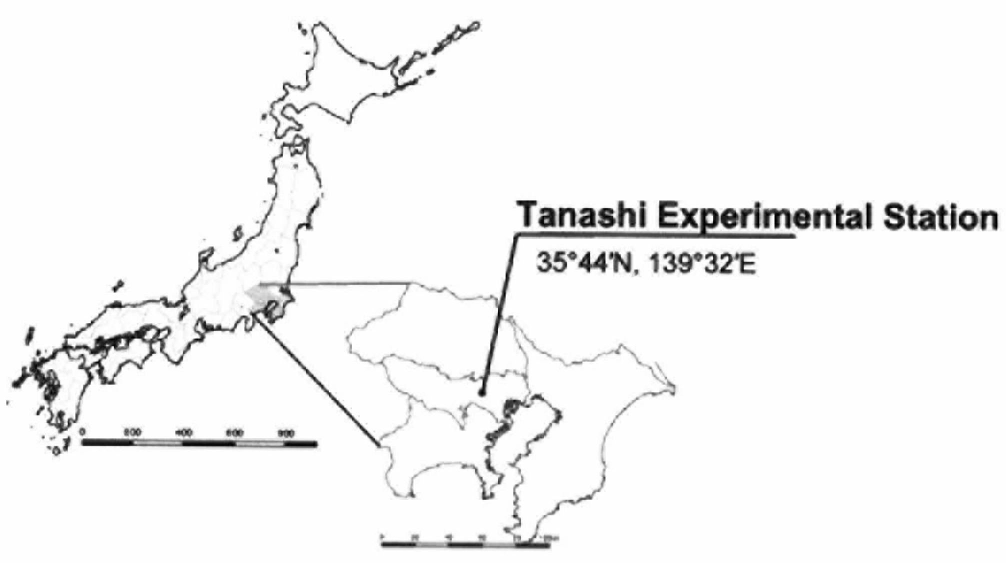


**Figure 4.1** Study site locations.

**Table 4.1** Characteristics of throughfall sites.

| | Species | Mean tree height (m) | First living branch height (m) | [a]Mean DBH (cm) | Canopy closure rate (%) |
|---|---|---|---|---|---|
| CY | Japanese cypress[b] | 11.6 | 5.8 | 23.4 | 83.6 |
| CD | Japanese cedar[c] | 16.6 | 6.3 | 23.7 | 88.6 |
| SO | Sawtooth oak[d] | 16.8 | 3.6 | 46.0 | 78.0 |

[a] Mean stem diameter at branch height.

[b] *Chamaecyparis obtusa.*

[c] *Cryptomeria japonica.*

[d] *Quercus acutissima* .

canopy species: 20-yearold Japanese cypress (*Chamaecyparis obtusa*), 40-year-old Japanese cedar (*Cryptomeria japonica*), and 40-year-old sawtooth oak (*Quercus acutissima*). I denote these sites by the acronyms CY, CD, and SO, respectively. The first two sites were plantations consisting of Japanese evergreen coniferous trees and the third was composed of deciduous broad-leaved tree cover. All four observation sites were approximately 100 × 150 m. Table 4.1 gives the tree characteristics of the throughfall sites. The canopy closure rate was determined using CanopOn 2 software (http://takenaka-akio.cool.ne.jp/etc/canopon2/) from hemispherical photographs taken at each site. The mean DBH (diameter at breast height) in SO was greater than those in the coniferous sites; light intensity in SO was higher because of less complete canopy closure.

*Data collection*

I measured the meteorological factors of rainfall intensity and wind speed at the open site. Rainfall intensity was measured with a 0.2-mm tipping bucket rain gauge (RC-10; Davis Instruments Corp., California, USA); tip time was recorded with 0.5-s accuracy by a data logger (HOBO Evnet; Onset Computer Corp., Bourne, MA, USA). Wind speed was measured once per minute at a height of 2 m above the ground with a three-cup anemometer (AC750; Makino Applied Instruments Corp., Tokyo, Japan) equipped with a data logger (SQ1250; Grant Instruments, Ltd., Cambridgeshire, UK). The distribution of raindrop size at each site was recorded by LD gauges version 2 (Fig. 2.5). The sampling area was 800 $mm^2$.

Five rainfall events were monitored during the observation period in June and July 2003. I analyzed three rainfall events with over 10 mm precipitation, named Events A–C. These three events were markedly different in terms of the meteorological factors (Table 4.2). Event A had low wind

**Table 4.2** Rainfall events.

| Event | Date (2003) | $W_{MEAN}$ (m $s^{-1}$) | $R_{MAX}$ (mm 10-$min^{-1}$) | Precipitation[c] (mm) | | | | Drop number[c] (in 800 $mm^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Open | CY | CD | SO | Open | CY | CD | SO |
| A | 13–14 July | 0.41 | 1.4 | 38.7 | 22.4 | 30.0 | 23.9 | 58,064 | 22,590 | 17,789 | 12,162 |
| B | 3–4 July | 0.86 | 4.0 | 25.5 | 12.4 | 18.1 | 20.6 | 21,982 | 11,830 | 12,347 | 14,747 |
| C | 8–9 August | 2.24 | 5.2 | 28.4 | 9.3 | 10.8 | 22.7 | 23,106 | 10,440 | 10,964 | 24,367 |

[a] Mean wind velocity.

[b] Maximum 10-min rainfall intensity.

[c] Precipitation and drop number were measured with LD gauges ver.2.

speed and low rainfall intensity, Event B had low wind speed but high rainfall intensity, and Event C had high wind speed and high rainfall intensity.

*Methods of analysis*

Throughfall-DSD varied with temporal variations in the meteorological factors. The process of forming throughfall drops in the canopy may be influenced by vibration of the canopy, described in *'Chapter 3'*. Since the canopy vibration was induced by wind and/or raindrop impact on to the canopy, I used wind speed and rainfall intensity as the meteorological factors influencing throughfall-DSD.

I used an hourly based data set for analysis. I gained 105 data sets in this observation. Fig. 4.2 shows the distribution of all hourly-based data sets on rainfall intensity (mm $h^{-1}$) and 5-min minimum wind speed (m $s^{-1}$). Minimum wind speed was determined by the minimum value of 5-min mean wind speed in 1 h. In Fig. 4.2, I show three meteorological condition groups delimited by the values of 1.0 m $s^{-1}$ in minimum wind speed and 2.0 mm $h^{-1}$ in rainfall intensity: the group labeled *Low* ($n$ = 71, with low rainfall intensity and low wind speed); the group labeled $R_{high}$ ($n$ = 21, with high rainfall intensity but low wind speed); and that labeled $W_{high}$ ($n$ = 12, with high wind speed but low rainfall intensity). The hourly data with high rainfall intensity and high wind speed was ignored because only one data item was recorded.

The DSD was based on the volume ratio normalized by the water volume. In order to separate the influence of canopy species and meteorological factors on throughfall-DSD, I evaluated throughfall-DSD under individual meteorological conditions and canopy species. From each DSD, I derived cumulative DSD and evaluated $D_{50}$, the median volume diameter. $D_{50}$ is a widely used

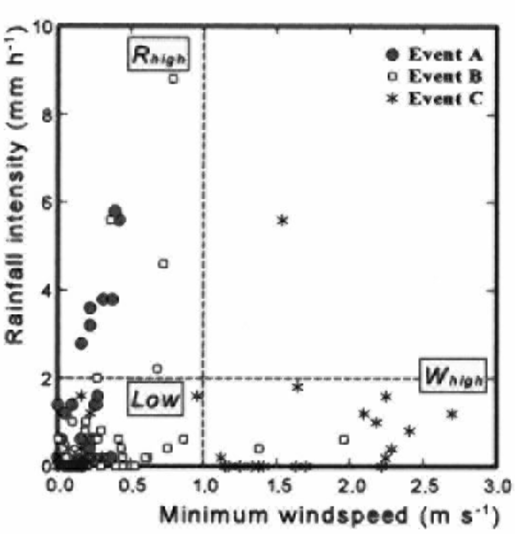


**Figure 4.2** Distribution of all hourly-based data sets on rainfall intensity and 5-min minimum wind speed. The *dashed lines* indicate boundaries of rainfall intensity and wind speed. The data in the *upper right* were not considered in this study.

index for representing open-DSD (Sempere-Torres et al., 1994) and throughfall-DSD (Hall and Calder, 1993). From the comparison of DSD and $D_{50}$ of different canopy species in *Low*, I calculated the influence of canopy species alone on throughfall-DSD because condition *Low* was little affected by the meteorological factors. From the comparison between *Low* and $R_{high}$, I evaluated the influence of rainfall intensity on throughfall-DSD, and from the comparison between *Low* and $W_{high}$, I determined the influence of wind speed on throughfall-DSD.

In addition to $D_{50}$, I also used the DSD difference to investigate the characteristics of the throughfall-DSD because throughfall had a bimodal DSD (Vis, 1986). The DSD difference was evaluated by subtracting the open-DSD from the throughfall-DSD to reflect the detailed variations of each peak in the bimodal distribution of the throughfall-DSD.

## 4.3 Results

*Throughfall-DSD*

Figures 4.3–4.5 respectively shows the data of Event A–C: the temporal variation of 1-min wind speed (m $s^{-1}$), 10-min rainfall intensity (mm 10-$min^{-1}$), and contour plans of drops per 10 min recorded at the four sites. Table 4.2 summarized the observed rainfall events. Fig. 4.6 shows the DSD during the overall observation period at the four observation sites, based on drop volume.

These table and figures confirm earlier results on throughfall-DSD (Vis, 1986). First, throughfall drops were fewer in number and larger in size at each forested site than at the open site rainfall. Second, there was a clear difference in DSD between open rainfall and throughfall. Open rainfall had a unimodal DSD, with the mode around 1 mm in diameter. Throughfall typically had a bimodal DSD, with the first mode around 1 mm in diameter and the second mode greater than 3 mm in diameter. I also confirmed the finding by Hall and Calder (1993) that throughfall had a different DSD depending on canopy species. In Fig. 4.4, the first mode was the same in the three species and in open rainfall, 1 mm in diameter, although the abundance ratios differed. The latter mode differed among the sites: CY had the smallest mode and SO had the largest mode. Recorded modes were 3.9, 4.5, and 5.1 mm in diameter at CY, CD, and SO, respectively (Fig. 4.6). The latter mode among canopy species was significantly different because the latter mode shifted with the bottom of the peak, while the first mode corresponded among canopy species. The throughfall drops at SO were larger than those at CD and CY.

*$D_{50}$ of each canopy species and meteorological conditions*

To compare throughfall-DSD among canopy species and meteorological factors, cumulative DSD (Fig. 4.7) and $D_{50}$ (Table 4.3) were evaluated at the four observation sites for the three meteorological conditions *Low*, $R_{high}$, and $W_{high}$ (refer to *'section 4.2'*). In Fig. 4.7b, the dotted horizontal lines show the 50% lines of cumulative DSD, and the dashed vertical lines indicate the $D_{50}$ of CD under the condition *Low*, 2.87 mm in diameter. With each meteorological condition and canopy specie, throughfall drops were larger than open rainfall drops.

Drop numbers were sufficient for comparison of each $D_{50}$. Of the 12 conditions (Table 4.3), 9

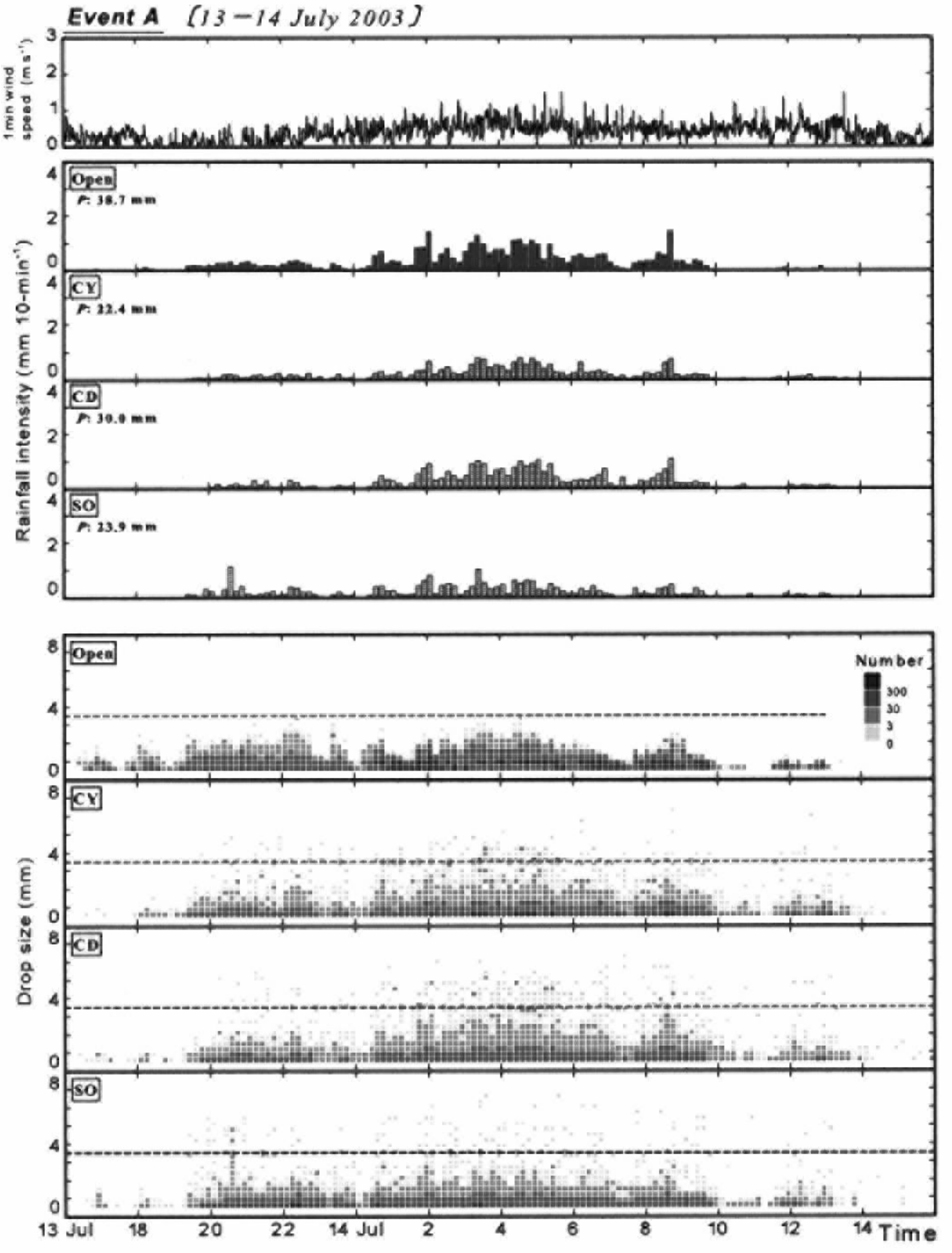


**Figure 4.3** Temporal variations in wind speed, rainfall intensity, and drop size at four observation sites in Event A. The drop size is shown in the contour plans with 0.3 mm in diameter class and 0.5 mm in minimum diameter per 10 min. The *dashed lines* indicate 3.5 mm, which was the maximum diameter class of open rainfall drops in Event A; *P* indicates the total precipitation for Event A.

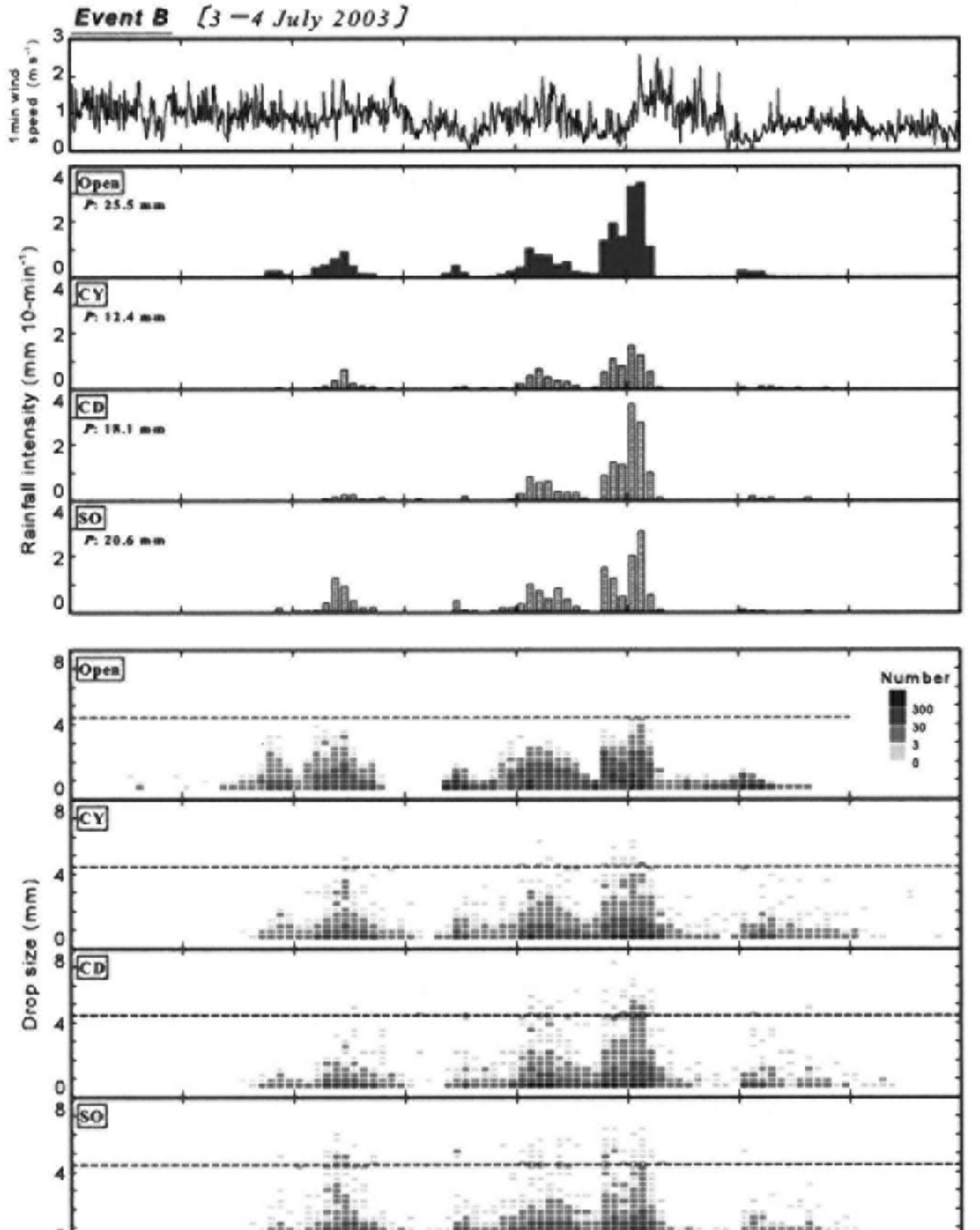


**Figure 4.4** Temporal variations in wind speed, rainfall intensity, and drop size at four observation sites in Event B. The *dashed lines* indicate 4.4 mm, which was the maximum diameter class of open rainfall drops in Event B.

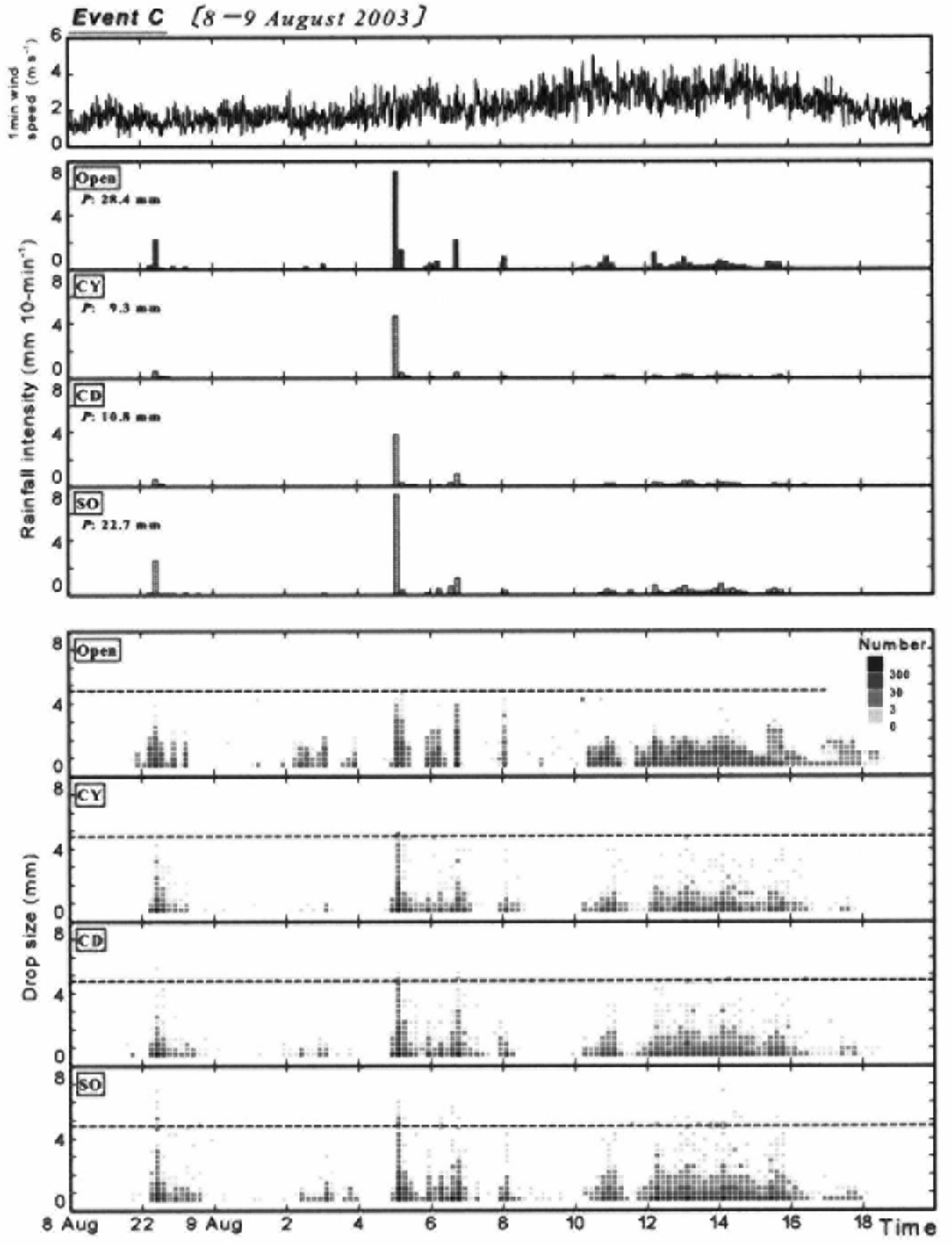


**Figure 4.5** Temporal variations in wind speed, rainfall intensity, and drop size at four observation sites in Event C. The vertical scales of wind speed and rainfall intensity are twice larger than Fig. 4.3 and 4.4. The *dashed lines* indicate 4.7 mm, which was the maximum diameter class of open rainfall drops in Event C.

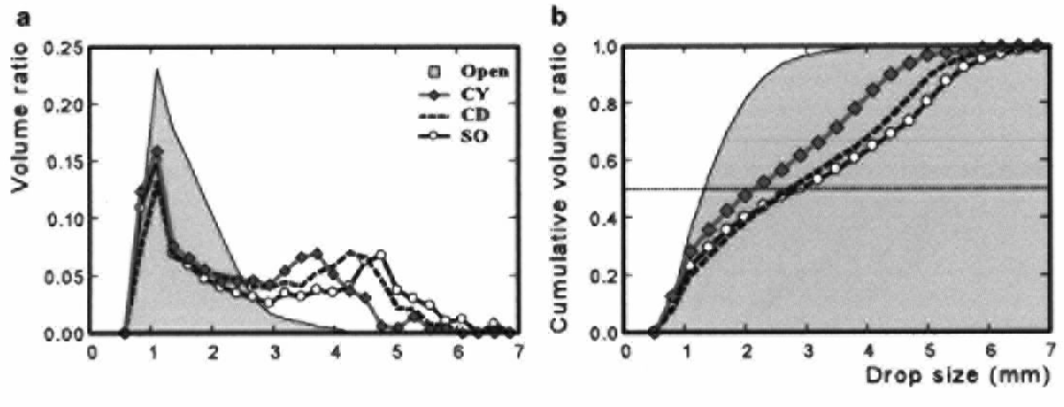


**Figure 4.6** **a** Drop size distributions (DSDs) at the four observation sites during the overall observation period, with 0.3 mm in diameter class and 0.5 mm in minimum diameter. Each DSD was normalized by the respective water volume. **b** Cumulative DSD. The *dashed horizontal line* indicates the 50% line of cumulative DSD.

**Table 4.3** $D_{50}$ and drop number of each sites under three meteorological conditions.

| | $D_{50}$ (mm) | | | | Drop number (in 800 mm$^2$) | | |
|---|---|---|---|---|---|---|---|
| | *Low* | $R_{high}$ | $W_{high}$ | Overall | *Low* | $R_{high}$ | $W_{high}$ |
| Open | 1.09 | 1.39 | 1.40 | 1.33 | 42,094 | 48,349 | 12,709 |
| CY | 2.00 | 2.14 | 1.77 | 2.15 | 12,797 | 27,939 | 4,124 |
| CD | 2.93 | 2.87 | 1.92 | 2.75 | 9,898 | 26,036 | 5,166 |
| SO | 3.60 | 2.77 | 1.88 | 2.88 | 17,390 | 32,417 | 11,469 |

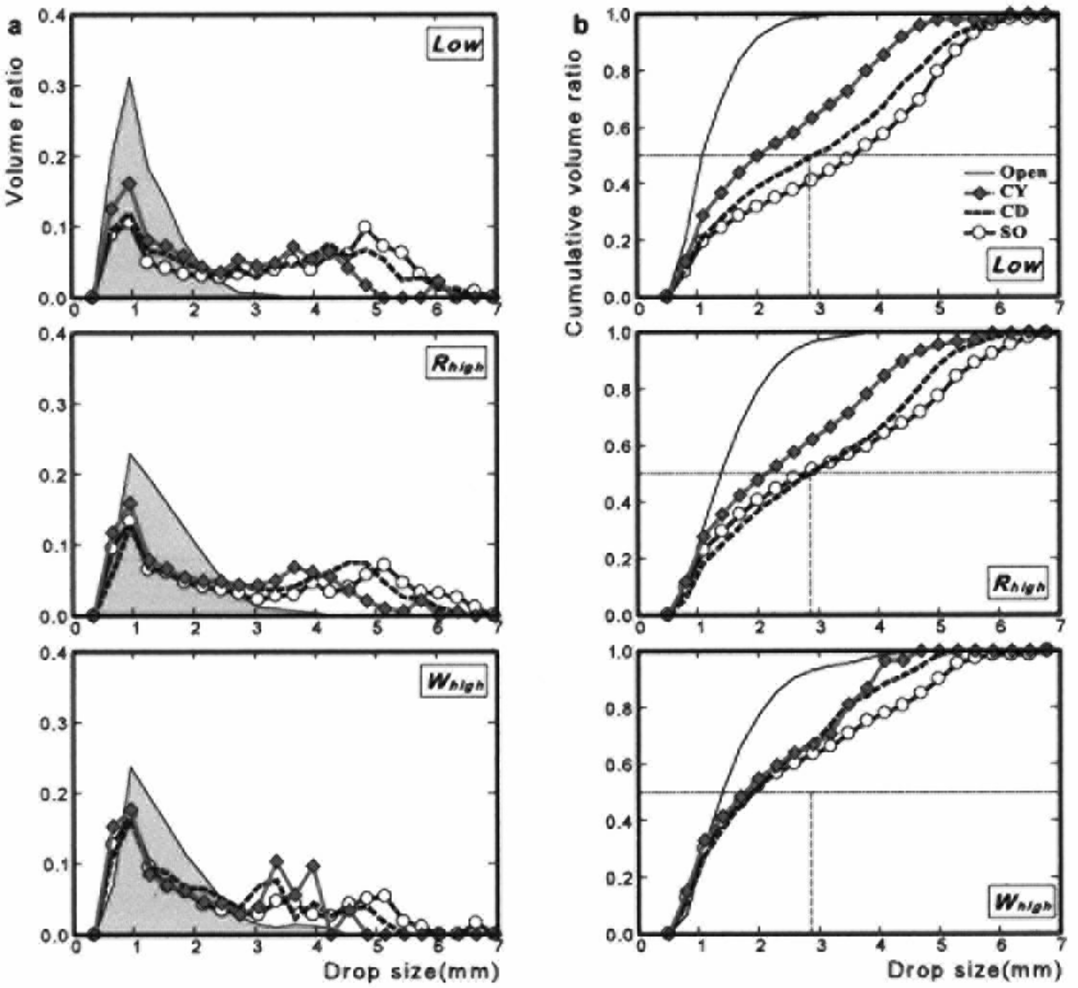


**Figure 4.7 a** Drop size distributions (DSDs) at the four observation sites for three meteorological conditions, categorized in Fig. 4.2. **b** Cumulative DSD. The *dotted horizontal lines* indicate the 50% lines of cumulative DSD. The *dashed vertical lines* indicate the $D_{50}$ of CD under the condition *Low*, 2.87 mm in diameter.

conditions had more than 10,000 drops, which is the required drop number for estimating the DSD and $D_{50}$ to 3% or less (Salles et al., 1999). Salles et al. (1999) reported that a $D_{50}$ of 4,000 drops had less than 0.03 of the coefficient of variation. Applying this result to conditions with less than 10,000 drops in this study, the range of fluctuation of $D_{50}$ was less than ± 0.05 mm.

The influence of canopy species on $D_{50}$ was evaluated by comparing *Low*. In *Low*, in which the influence of rainfall intensity and wind speed was low (Fig. 4.7 and Table 4.3), $D_{50}$ differed among the canopy species. SO showed larger drops and CY smaller drops for all three canopy species.

The influence of rainfall intensity on $D_{50}$ was evaluated by comparing *Low* and $R_{high}$ (Fig. 4.7 and Table 4.3). For open rainfall, $D_{50}$ was larger with higher rainfall intensity, as was also found in earlier studies (Marshall and Palmer, 1948; Sempere-Torres et al., 1994; Uijlenhoet and Stricker, 1999). $R_{high}$ had 0.30 mm larger $D_{50}$ than *Low*. However, for throughfall, CY and CD had approximately the same $D_{50}$ as both *Low* and $R_{high}$. Mosley (1982) and Vis (1986) also showed that throughfall typically has a DSD independent of rainfall intensity. In contrast, $D_{50}$ in SO was different; $R_{high}$ had a $D_{50}$ value 0.83 mm lower than *Low*. SO had a higher $D_{50}$ than CD in *Low*, but had lower $D_{50}$ than CD in $R_{high}$.

The influence of wind speed on $D_{50}$ was evaluated by comparing *Low* and $W_{high}$ (Fig. 4.7b and Table 4.3). For open rainfall, $D_{50}$ was higher under windy conditions than under still air conditions. $W_{high}$ had a $D_{50}$ value 0.31 mm higher than *Low*. A similar result was also observed in an experiment involving simulated rain in a wind tunnel (Erpul et al., 1998). However, for throughfall, $D_{50}$ was lower in $W_{high}$ than *Low* for each canopy species. The difference in $D_{50}$ between *Low* and $W_{high}$ was -0.23 mm in CY, -1.01 mm in CD, and -1.72 mm in SO. SO showed a greater change than CD or CY. The occurrence frequency of larger drops exceeding 3 mm in diameter was different, but $D_{50}$ had a similar value for each of the three canopy species.

*DSD difference between open rainfall and throughfall*

Fig. 4.8 shows the DSD differences of the three canopy species under *Low*, $R_{high}$, and $W_{high}$ conditions. The DSD difference was calculated by subtracting the open-DSD from the throughfall-DSD. Positive values indicate that throughfall has a higher value than open rainfall. In Fig. 4.8, there are two peaks with positive values for drops less than 1 mm in diameter and for drops exceeding 2 mm in diameter. Regarding the peak with the smaller diameter, it was not present for *Low* but was observed for $R_{high}$ and $W_{high}$ (white arrows in Fig. 4.8). In particular, under $W_{high}$, each canopy species showed that peak and the amount was larger than for $R_{high}$. Heavy rain and especially strong wind would be expected to produce smaller drops than open rainfall. Regarding the peak with the larger diameter, which indicates drops with larger size than for open rainfall, more larger drops were present than smaller drops. Table 4.4 shows the abundance ratio of drops exceeding 2 mm in diameter in Fig. 4.8. The amount ratio reduced in both $R_{high}$ and $W_{high}$ compared to *Low*, but relatively smaller drops were generated in $W_{high}$.

## 4.4 Discussion

*Throughfall drop components*

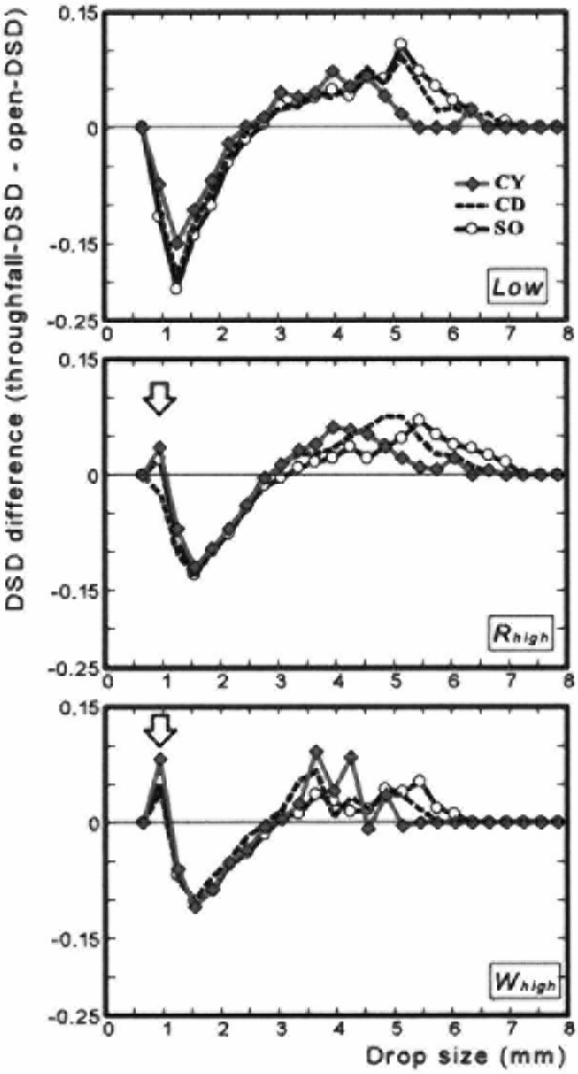


**Figure 4.8** DSD difference at the three throughfall observation sites for the three meteorological conditions. The DSD difference was calculated by subtracting the open-DSD from the throughfall-DSD of Fig. 4.7a. Positive values indicate that throughfall was higher than open rainfall.

**Table 4.4** The abundance ratio of drops exceeding 2 mm in diameter in Fig. 4.8.

| | *Low* | $R_{high}$ | (vs. *Low*) | $W_{high}$ | (vs. *Low*) |
|---|---|---|---|---|---|
| CY | 0.417 | 0.361 | (−13.5%) | 0.281 | (−32.7%) |
| CD | 0.556 | 0.476 | (−14.4%) | 0.275 | (−50.5%) |
| SO | 0.626 | 0.433 | (−30.9%) | 0.316 | (−49.5%) |

The DSD difference (Fig. 4.8) showed two positive peaks for drops less than 1 mm in diameter and for drops exceeding 2 mm in diameter. These peaks indicate that various components were contributing to the throughfall-DSD. Drops of the higher peak, which were higher than open rainfall, might have consisted of drips from the canopies; raindrops would coalesce in the canopy, forming larger throughfall drops. Meanwhile drops of the lower peak, which were smaller than open rainfall, might consist of splash droplets, produced by raindrop impact onto canopies, and spattering water caused by wind vibration in the canopies. I believe that water draining from the canopy consisted of splash droplets as well as coalesced drips.

*Variations in throughfall DSD*

When the influence of meteorological factors was low, throughfall had a different DSD and $D_{50}$ among the canopy species (Fig. 4.7 and Table 4.3). This suggests that the canopy species themselves may have different capacities to produce large drips, independently of meteorological factors. Fig. 4.9 shows pictures of leaves from the three canopy species, CY, CD, and SO. Broad-leaved trees with large water storage area per leaf, such as SO, could form larger drips through rainwater coalescing on the leaf surfaces. Coniferous trees with fine scale-like leaves, such as CY, could only produce smaller drips because rainwater could not coalesce readily on the leaves. When little vibration of the canopy is present, with low rainfall intensity and wind speed, the difference in the ease of formulating large drips may induce the differences of DSD and $D_{50}$ among canopy species.

Throughfall drops became smaller under windy conditions than under still air conditions for all three canopy species (Fig. 4.7 and Table 4.3). This may have been induced by the simultaneous increase in splash droplets (the white arrow in Fig. 4.8) with the decrease in drips (Table 4.4). Strong wind induces severe vibration of the canopy, which produces an increase in spattering rainwater from canopies and a decrease in the size of each drip because canopy vibration reduces the amount of water coalescing and forces water dripping in canopies. Meanwhile, throughfall drops became smaller in high rainfall intensity conditions for SO but scarcely changed for CY and CD (Fig. 4.7 and Table 4.4). Heavy rain also increased splash droplets through the increase in raindrop impact energy onto the leaves, but the effect was lower on the throughfall-DSD than that of wind speed. The impact of meteorological forces was different among the canopy species. Those species like SO, which produce larger throughfall drops naturally, with little meteorological force, could be more easily influenced by vibration of the canopy than those like CY, which produce smaller throughfall drops.

*A process for generating the throughfall drop size distribution*

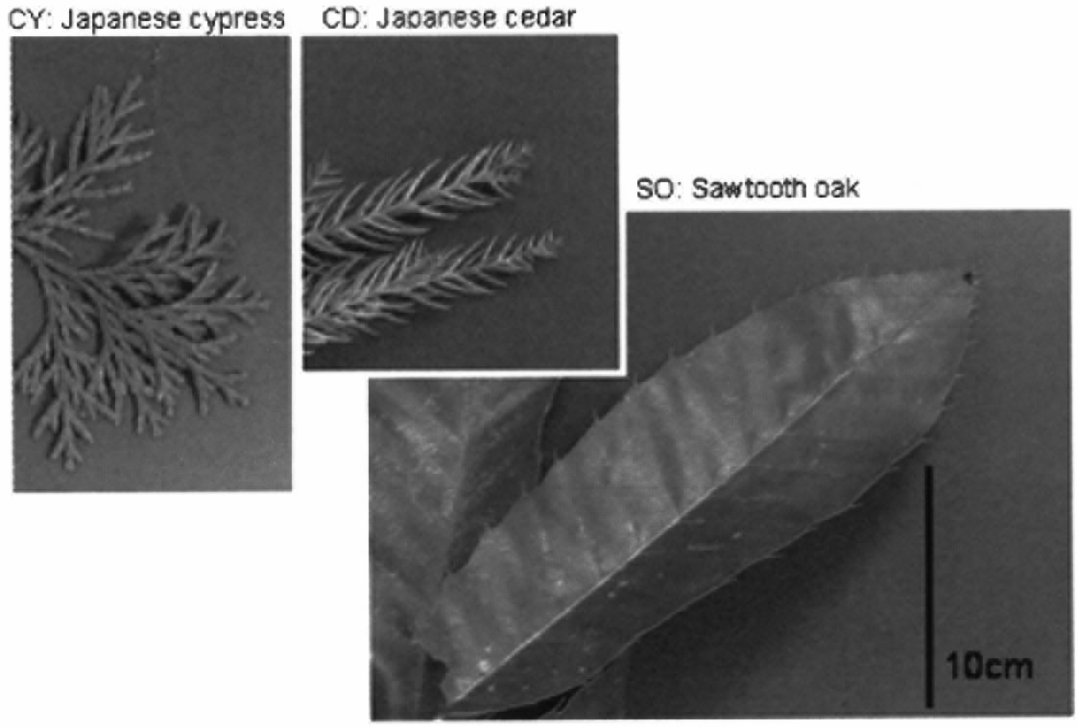


**Figure 4.9** Leaf apexes of CY, CD, and SO. SO had a large surface area per leaf. CY and CD had fine scale-like leaves.

In the interception models (Rutter et al., 1971; Gash, 1979), including a two-layer stochastic model (Calder, 1996), throughfall has been separated into two components; free throughfall, raindrops passing through canopies without striking the vegetation, and drainage water from canopies. They assumed that drainage water from canopies fell only as drips. Throughfall-DSD was generated from a combination of free throughfall-DSD and drip DSD (Hall, 2003).

I suggest a modified process for generating throughfall-DSD, reflecting the results obtained in this study. Figure 4.10 shows a schematic diagram of this process. A splash component has been added to the process described by Hall (2003). Throughfall-DSD is produced by the combination of three drop components: free throughfall, splash droplets, and drips. When the amount ratio and the size distribution of each component are determined, throughfall-DSD can be evaluated.

For free throughfall, the amount ratio is determined by the free throughfall coefficient ($p$), which is one of the main parameters in interception models (Rutter et al., 1971; Gash, 1979; Calder, 1996). The value of $p$ would be reflected in the canopy gap fraction, but it is known that p fluctuates among rainfall events (Link et al., 2004) and wind speed (Kuraji et al., 2001). Free throughfall would have the same DSD as open rainfall drops, which is determined by meteorological factors such as rainfall intensity, type of rainstorm, and wind speed (Marshall and Palmer, 1948; Joss and Waldvogel, 1967; Sempere-Torres et al., 1994; Erpul et al., 1998). Open-DSD can be related to rainfall intensity through a simple power law.

Splash droplets are smaller than open rainfall drops. The amount of splash droplets increases

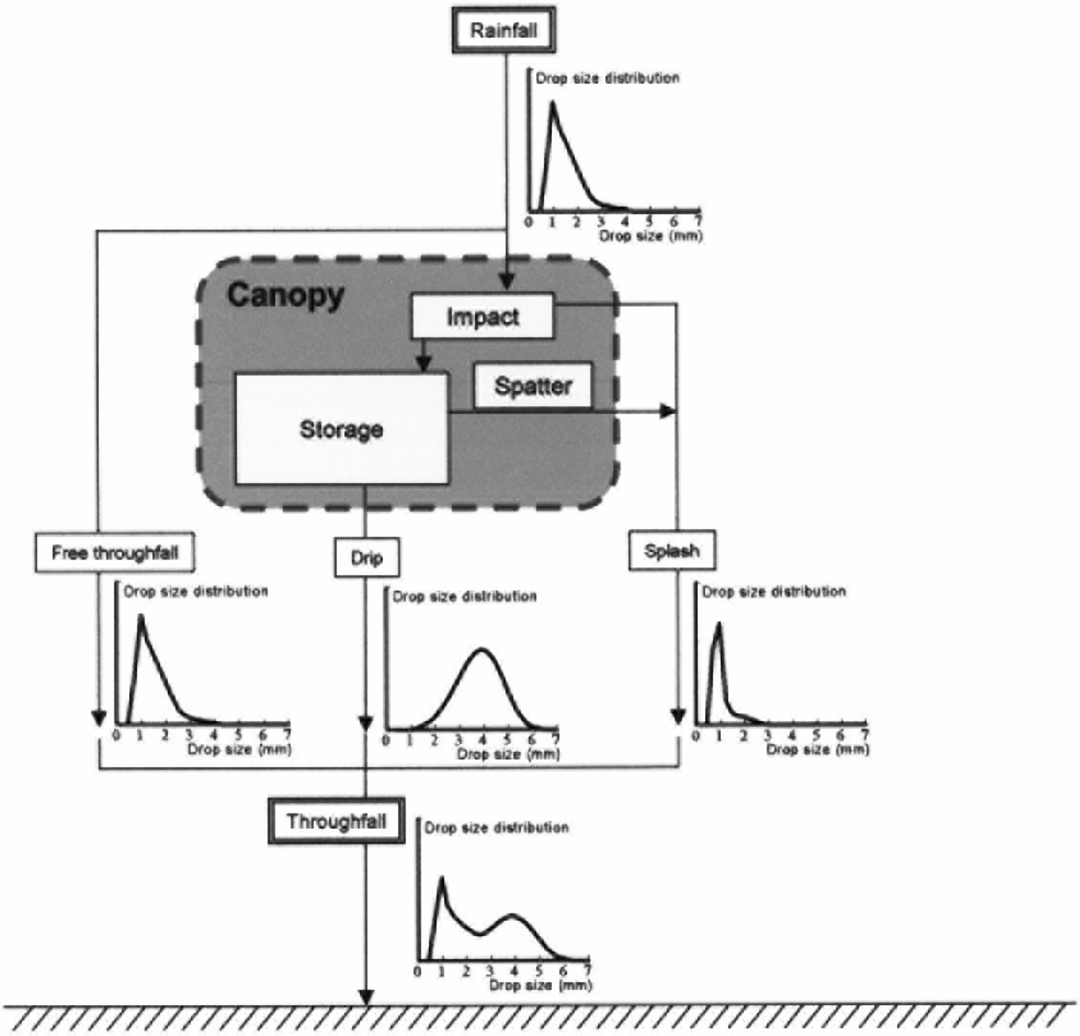


**Figure 4.10** Schematic diagram illustrating the components generating throughfall-DSD.

with rainfall intensity, since it relates to the increase of rain-splash on the canopy caused by raindrop impact (Yang and Madden, 1993; Saint-Jean et al., 2004; Murakami, 2006), and also increases with wind speed because of the increase in spattering water caused by vibration of the canopy. The DSD of splash was well fitted by the Weibull distribution function, and the Weibull parameters were largely dependent of rainfall intensity (Yang and Madden, 1993).

Drips are larger than open rainfall drops. The amount of drips is associated with canopy water storage ($S$), which is the other main parameter in interception models. $S$ decreases with wind speed through the decrease in the water retention capacity of leaves (Herwitz, 1985; Hutchings et al., 1988; Llorens and Gallart, 2000). This causes an increase in the splash amount and a simultaneous decrease in the drip amount. The DSD of drips has not previously been approximated by a distribution function. Our results and those of Brandt (1989) have shown that the mode of the distribution moves toward a larger size than that of the normal distribution. The DSD of drips varies in a manner strongly influenced by wind speed.

## 4.5 Conclusions

Drop size distributions (DSDs) were continuously measured in an open site and in three forest stands simultaneously during three rainfall events in Tokyo, Japan. Drop size data obtained during the whole observation period were used in an hourly based data set and divided into three groups depending on three meteorological conditions: calm, heavy rain, and strong wind. Evaluating the influence of canopy species and meteorological factors using $D_{50}$ and DSD differences revealed some throughfall-DSD characteristics.

First, throughfall had different DSDs among canopy species under conditions of little vibration of the canopy, with low rainfall intensity and wind speed; $D_{50}$ values were 2.00, 2.93, and 3.60 mm in CY, CD, and SO, respectively. Differences were produced by the varying natural capacities of the canopies to produce large drips. Second, throughfall contained smaller drops under severe vibration of the canopy conditions, with high rainfall intensity and/or high wind speed, than under calm meteorological conditions. Vibration of the canopy led to reduced water coalescence and an increase in the spattering of rainwater from canopies. Wind speed had a greater effect on throughfall-DSD variations than did rainfall intensity. Third, the influence of meteorological factors was different among the canopy species; SO was readily influenced but CY was not.

Moreover, it was implied in the results that throughfall consisted of three components: free throughfall, drips and splash droplets. This study determined a process for generating throughfall-DSD that could explain the variations in throughfall-DSDs among canopy species and the influence of meteorological factors.