29 Fog interception in a Puerto Rican elfin cloud forest: a wet-canopy water budget approach

F. Holwerda, L. A. Bruijnzeel, A. L. Oord
VU University, Amsterdam, the Netherlands

F. N. Scatena
University of Pennsylvania, Philadelphia, Pennsylvania, USA

ABSTRACT

Between 10 July and 25 October 2001, fog interception (*CWI*) by a Puerto Rican elfin cloud forest at 970 m.a.s.l. was studied. Values of *CWI* were estimated from the wet-canopy water budget as the sum of throughfall, stemflow, and interception loss, minus rainfall corrected for the effect of slope. *CWI* was also estimated from throughfall measurements during periods of fog-only. Timing and duration of fog were measured using a wire harp that was protected against rainfall. Estimated rates of *CWI* correlated significantly ($p < 0.01$) with collections by the fog gage. Gage to canopy factors were determined from the slopes of these relationships and were considered to integrate differences in fog-catching efficiency of the wire harp and the forest canopy. Applying these factors to the fog gage record yielded an estimated 1.1–1.4 mm day^{-1} of fog *CWI*, equivalent to 10–12% of mean daily corrected rainfall (11.3 mm day^{-1}). The wet-canopy water budget method gave the best results when rainfall amounts were small compared to fog, but error bands of estimated *CWI* became too wide to give meaningful results when rainfall was equal to or larger than the amount of fog. Furthermore, solving the water budget for large rainstorms gave negative values of *CWI*, possibly because of underestimated stemflow.

INTRODUCTION

Although the hydrological importance of tropical montane cloud forest (TMCF) has become increasingly recognized during the last two decades (Zadroga, 1981; Bruijnzeel, 2005), reliable estimates of cloud water (fog) interception (*CWI*) by TMCF are still relatively scarce (reviewed by Bruijnzeel, 2005). A common approach is to compare amounts of throughfall (*TF*) plus stemflow (*SF*) with amounts of incident rainfall (*P*) during periods with and without fog (Harr, 1982; Schellekens *et al.*, 1998; Holder, 2003; cf. McJannet *et al.*, 2007). Because wet-canopy evaporation losses are typically neglected, this technique provides a minimum estimate of *CWI* (see Bruijnzeel, 2005 for discussion). Furthermore, because TMCF often occurs on wind-exposed ridges or mountain peaks where rain tends to fall at an angle for much of the time, the effective depth of rainfall incident to sloping ground differs from that indicated by measurements made with a conventional rain gage (Sharon, 1980; cf. García-Santos and Bruijnzeel, this volume; Giambelluca *et al.*, this volume). Also, rainfall measurements by gages raised above ground level are subject to systematic error because of the distorted wind field above the gage orifice (Sevruk, 1982). As such, rainfall measurements at TMCF sites may be subject to large uncertainty, which further complicates quantification of *CWI* via comparative measurements (cf. Blocken *et al.*, 2005; Frumau *et al.*, 2006; Holwerda *et al.*, 2006a; Mulligan *et al.*, 2006). The proper quantification of *TF* requires large numbers of gages to account for the high spatial variability of tropical forest canopies and the use of "roving" gages has been recommended to increase the sample area and reduce the error (Lloyd and Marques, 1988; Holwerda *et al.*, 2006b). However, the roving gage method has been little used so far in TMCF (Bruijnzeel, 2005; cf. Fleischbein *et al.*, this volume), and errors in published estimates of *CWI* based on conventionally measured *TF* are likely to be substantial (cf. Hafkenscheid *et al.*, 2002; Holwerda *et al.*, 2006b; Prada *et al.*, 2009).

Tropical Montane Cloud Forests: Science for Conservation and Management, eds. L. A. Bruijnzeel, F. N. Scatena, and L. S. Hamilton. Published by Cambridge University Press.

Modeled estimates of fog deposition in complex terrain show pronounced spatial variability (Walmsley *et al.*, 1996; Mulligan and Burke, 2005), as do comparative studies using differently exposed fog gages (e.g. Juvik and Ekern, 1978; Cavelier *et al.*, 1996; cf. González, this volume). However, field studies of small-scale spatial variability of *CWI* inferred from net precipitation (i.e. *TF* + *SF*) measurements in TMCF of contrasting exposition are rare (e.g. Weaver, 1972; Stadtmüller and Agudelo, 1990; García-Santos, 2007; Prada *et al.*, 2009; Giambelluca *et al.*, this volume; Häger and Dohrenbusch, this volume). This chapter reports on a study of *CWI* in an elfin cloud forest at 970 m.a.s.l. in the Luquillo Mountains of Puerto Rico between 10 July and 25 October 2001. The present data complement an earlier study at the nearby but more exposed Pico del Este (Holwerda *et al.*, 2006a).

STUDY AREA

The measurements were made in a 0.54-ha watershed situated *c.* 200 m east-northeast of Pico del Oeste (1020 m.a.s.l.) in the eastern Luquillo Mountains of Puerto Rico (Figure 29.1). The watershed is located between 950 and 990 m.a.s.l. in the headwaters of the Rio Abajo. It has an easterly aspect, and a mean slope of ~11°. The area is mainly covered with 2–5 m tall (on average ~3 m) elfin cloud forest dominated by *Tabebuia rigida* and *Ocotea spathulata* with an estimated leaf area index of 2.0–3.5 (Weaver, 1995). The forest is rich in epiphytes, with mosses and bromeliads covering branches, stems, and part of the soil surface (Weaver, 1972). Small fragments of palm forest occur along the lower reaches of the stream channel.

Meteorological parameters were measured above the canopy at nearby palm forest (900 m.a.s.l.) and elfin cloud forest (1010 m.a.s.l.) sites (see Figure 29.1 for locations). The palm forest site is dominated by Sierra palm (*Prestoa montana*) with a mean height of ~6 m (Holwerda, 2005) whereas the forest near Pico del Este (Weaver, 1995; Holwerda *et al.*, 2006a) is very similar to that of the study watershed. Mean annual rainfall is about 4500 mm (Baynton, 1968; García-Martinó *et al.*, 1996). On average, most rainfall occurs in May, October, and November (450–500 mm each), whereas January, February, and March typically receive 250–300 mm each (García-Martinó *et al.*, 1996). Mean monthly temperatures vary from *c.* 17 °C in January–February to *c.* 20 °C in September–October (Baynton, 1968; Brown *et al.*, 1983) whereas the mean relative humidity is very high at about 98% (Weaver, 1995). The prevailing trade winds blow mainly from the east; the mean monthly wind speed at Pico del Oeste is 4–5 m s^{-1} (Baynton, 1968). Fog is very common. On Pico del Oeste, Baynton (1968) reported fog to persist for *c.* 60% of the time during the day and for nearly 100% of the time at night. At Pico del Este, fog was observed for about 75% and 95% of the time during the day and at night, respectively, between 25 June

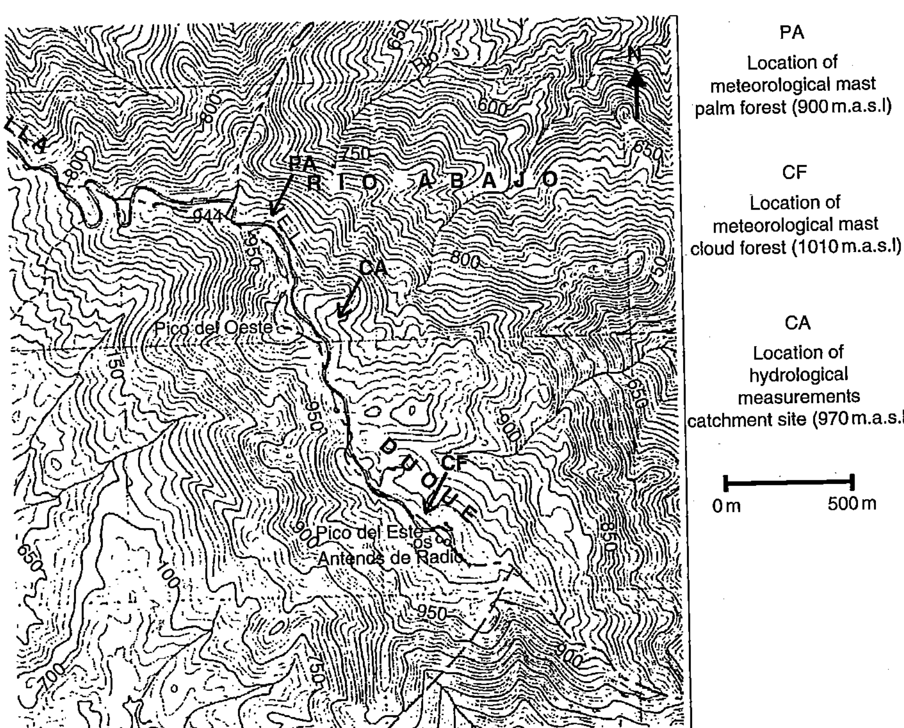

Figure 29.1. Location of climatic masts in the palm forest (900 m.a.s.l.) and the elfin cloud forest (1010 m.a.s.l.), and location of hydrological measurements (970 m.a.s.l.) near Pico del Oeste, Luquillo Mountains, Puerto Rico. Spacing of contour lines is 10 m.

and 7 August 2005 (Holwerda *et al.*, 2006a; cf. Holwerda *et al.*, this volume #28).

METHODS

General climatic measurements

Continuous climatic measurements were made in 7.5 m and 12 m tall masts placed at the nearby palm and cloud forest sites (Figure 29.1), respectively, using identical instrumental set-ups. Measurements included incoming and outgoing short- and long-wave radiation to give net radiation, wind speed and direction, as well as temperature and relative humidity. For instrumental details see Holwerda (2005). Climatic parameters for the *CWI* study site (970 m.a.s.l.) were calculated as the means of those measured at the palm (900 m) and cloud forest (1010 m) sites.

Rainfall

Rainfall (P, mm) was measured at the center of the watershed with a tipping bucket rain gage (P_{tb}, manufactured at the Vrije Universiteit Amsterdam, 500 cm^2 orifice at 1.5 m above the ground, 0.10 mm per tip) connected to a data-logger that registered rainfall to the nearest second; recordings were converted later to the hourly totals used in this analysis. Rainfall was also measured with two totalizing rain gages (P_{t1}, P_{t2}, 100 cm^2 orifice at 0.3 m, and spaced about 100 m apart). The two totalizers were read at the same time as the throughfall gages (typically every 3 days). Each rain gage was placed at a relatively sheltered site with the mean angle between gage orifice and the surrounding tree tops being less than 20°. Readings from the two totalizers agreed very well ($P_{t2} = 1.01P_{t1} - 0.28$, r2 = 1.00, $n = 33$), and were c. 3% lower than amounts measured by the recording gauge ($P_{t1} = 0.97P_{tb} - 0.90$, r2 = 1.00, $n = 37$). Wind-induced errors were considered negligible for P_{t1} and P_{t2}, as the gages were close to ground level and relatively sheltered. Wind effects may have affected measurements by P_{tb} because of its more elevated position. The slightly higher catch of P_{tb} compared to P_{t1} and P_{t2} is somewhat suspect, therefore, and may be due to gage calibration errors. Because agreement between P_{t1} and P_{t2} was excellent, their readings were averaged and used as a reference for P_{tb}.

The intensity at which rain is intercepted by a given surface depends on the angle of incidence, i.e. it is highest when rain falls normal to the surface, and becomes lower when rain falls at an angle (Sharon, 1980). The rain gage orifices were installed horizontally at a slope of about 11° that was orientated perpendicularly to the easterly trade winds (Figure 29.1). Because of the relatively windy conditions, rain fell at an angle for much of the time, and the actual rainfall incident to the forest canopy must therefore have been higher than that measured by the gages. A trigonometric model was used to compute the rainfall normal to a slope (P_a) from conventional (horizontal orifice) rainfall (P) measurements (Sharon, 1980). For each event, the median rainfall inclination was calculated using relationships between rainfall intensity, raindrop size, terminal fall velocity of the rain drops, and wind speed (Holwerda *et al.*, 2006a). Rainfall events were defined as being separated by a dry period of at least 3 hours (Schellekens *et al.*, 1998). In applying the Sharon (1980) model, it was assumed that the canopy surface runs parallel to the sloping ground, and that the proportion of the rain reaching the ground without touching the vegetation is negligible (cf. Holwerda *et al.*, 2006a).

Fog

Fog occurrence was measured in the center of the watershed with a 0.5 × 0.5 m wire harp (Goodman, 1985) orientated perpendicularly to the prevailing winds at a height of 3 m above the ground. The fog gage was protected from rainfall by a 2 × 2 m cover placed ~3 cm above the gage and slanting slightly in a N240E direction. A 50 × 6 cm gutter at the bottom of the gage led the collected cloud water to a tipping bucket (5 ml capacity) and logger device. Hourly amounts of fog collected by the gage (litres) were converted to depth equivalent (CWI_g, mm) by dividing through the gage collecting area.

Throughfall and stemflow

Throughfall (*TF*) was measured using 67 totalizing rain gages (100 cm^2 each). For 45 of the 67 gages, a roving sampling technique was used. Three transects of 79, 63, and 37 m length were outlined with numbered flags placed at 1-m intervals, representing 80, 64, and 38 possible sampling positions, respectively. These 182 sampling positions were divided into 45 groups of 4–5 neighboring positions. Within each group, a gage was placed by randomly selecting one of the 4–5 possible sampling positions; this procedure was repeated each time the gages were emptied (typically every 3 days). The remaining 22 gages were placed at fixed but randomly chosen positions, and were emptied at the same time as the roving gages. In addition, three steel gutters (projected surface areas of 0.98, 0.90, and 1.03 m^2, placed at an angle of ~18°) were used to obtain continuous records of canopy drip. The gutters were equipped with custom-built tipping bucket (50 ml capacity) and logger devices (recording to the nearest second). Gutter recordings were converted to hourly totals and averaged. Readings from the 67 totalizing gages were used as a reference for the mean record of the gutters. Because no separate stemflow (*SF*, mm) measurements were made, the previously recorded value of 5% obtained by Weaver (1972) for this forest type was used throughout.

Rainfall interception loss

Interception loss (E_i, mm) was calculated using the analytical model of Gash (1979) for corrected rainfall (P_a). Application of the model required the determination of the following canopy parameters: (i) canopy saturation value (S, mm), i.e. the amount of water left on the canopy when *TF* has ceased; (ii) "direct" *TF* coefficient (p), i.e. the proportion of the rain which falls to the ground without touching the vegetation; (iii) trunk water capacity (S_t, mm); and (iv) the proportion of P_a diverted to stemflow *SF* (p_t). Values of S were determined using the method of Leyton *et al.* (1967) for storms ≥ 1.5 mm. Because under foggy conditions, amounts of *TF* will be raised, only (nearly) fog-free rainfall events were selected for this analysis. The same constraint applied to events used for the determination of p using the method of Jackson (1975) for storms ≤ 1 mm. Evaporation from the trunks was not considered, i.e. S_t was assumed negligible. The mean *SF* fraction of 0.05 was used for p_t. The Gash (1979) model also requires information on the average rainfall intensity falling onto a saturated canopy ($\overline{R_a}$, mm hour^{-1}, taken from the recording gage and corrected for the effect of slope), and the average evaporation rate from the wet canopy ($\overline{E_w}$, mm hour^{-1}) which was calculated using the wet variant of the Penman–Monteith equation (Monteith, 1965). The condition of a saturated canopy is usually maintained when $\overline{R_a}$ exceeds 0.5 mm hour^{-1} (Gash, 1979).

Cloud water interception

Cloud water interception (*CWI*) was calculated from the wet-canopy water budget for each rainfall event j:

$$CWI_{\mathrm{wb},j} = TF_j + SF_j + E_{i,j} - P_{aj} \tag{29.1}$$

with the remaining terms as defined previously. In addition, for each period j with fog-only, fog interception ($CWI_{\mathrm{tf},j}$) was equated to the corresponding amount of throughfall TF_j. Fog events were defined as being separated by 3 hours without fog to allow canopy drying before the next event. In case a fog-only period was preceded by rainfall, the first 3 hours were excluded to avoid contributions by rain-induced *TF*. Because *SF* was not measured, it was neglected in the calculations of CWI_{tf}.

STANDARD ERRORS

The standard error (SE) of $CWI_{\mathrm{wb},j}$ was determined from the errors in the respective budget components using:

$$\mathrm{SE}_{CWI_{\mathrm{wb}j}} = \sqrt{\mathrm{SE}^2_{TFj} + \mathrm{SE}^2_{SFj} + \mathrm{SE}^2_{\mathrm{E}_{ij}} + \mathrm{SE}^2_{\mathrm{P}_{aj}}} \tag{29.2}$$

in which $\mathrm{SE}_{x,j}$ is the standard error in water equivalent (mm) for a water budget component x per rainfall event j. For those components for which no SE could be calculated (*SF* and E_i), the error equaled the estimated or calculated value for that component. The error in P_a was estimated as the difference between the catch of totalizers P_{t1} and P_{t2} (i.e. 1% of P_a) plus the slope correction itself. The SE of mean *TF* was calculated from the distribution of the catch of the 67 individual gages per sampling interval.

RESULTS

Fog occurrence in relation to climatic conditions

Rates of cloud water collection by the wire harp showed a distinct diurnal pattern (CWI_g, Figure 29.2f). Collection rates were usually highest at night (0.5–0.6 mm hour^{-1}) and decreased rapidly after sunrise to less than 0.2 mm hour^{-1} during the day. Although this pattern is partly related to that of wind speed U (Figure 29.2c), it also indicates that fog was almost continuously present at night due to the lowering of the cloud base caused by nocturnal cooling. During the day, however, the cloud base would sometimes rise above the elevation of the site due to daytime heating. Between 10 July and 25 October 2001, the mean amount of fog collected by the wire harp was 9.0 mm day^{-1} (Table 29.1). Out of the 100 days with data, 99 days had fog and only one day was entirely fog-free. Overall fog occurrence was 73% of the time (55% and 89% during day- and night-time conditions, respectively). Defining fog events as being separated by a fog-free period of at least 3 hours yielded 64 events with a mean duration of 27 hours (Table 29.1). The mean amount of fog intercepted by the wire harp per event was 14.1 mm. The most prolonged event lasted 188 hours (*c.* 8 days, 14–22 October 2001), during which time the wire harp intercepted a total of ~135 mm of fog.

Mean diurnal patterns of net radiation (R_n), temperature (T), wind speed (U), wind direction (U_{dir}), and relative humidity (*RH*) between 10 July and 25 October 2001, as calculated from the data collected at the two nearby climatic stations, are shown in Figure 29.2. The daily pattern of R_n (Figure 29.2a) shows that cooling at night by eradiation was hampered by the persistence of fog (Figure 29.2f). The low value of mean midday R_n (*c.* 300 W m^{-2}, Figure 29.2a) indicates that fog or clouds also attenuated much of the incident radiation during the day. This resulted in a small difference (*c.* 1.5 °C) between mean maximum and minimum T (Figure 29.2b). At night *RH* was close to 100%, while the mean midday value was about 95% (Figure 29.2e), again indicating that fog was usually heavier and more persistent at night than during the day. Winds were predominantly from the east (Figure 29.2d) and somewhat stronger at night than during the day (2.8–3.0 m s^{-1}, Figure 29.2c).

Rainfall

Mean daily rainfall between 10 July and 25 October 2001 was 10.9 mm day^{-1} (Table 29.2), and from the 97 days with data,

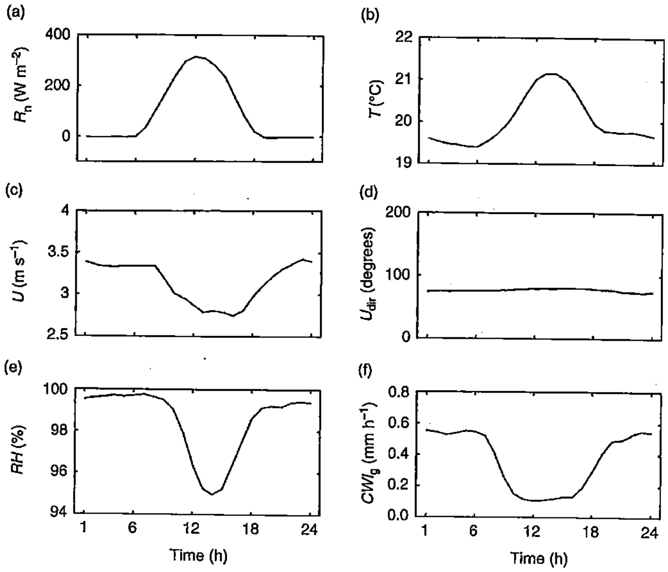

Figure 29.2. Mean diurnal patterns of (a) net radiation (R_n), (b) temperature (T), (c) wind speed (U), (d) wind direction (U_{dir}), and (e) relative humidity (RH), as calculated from data of two nearby climatic stations (see Figure 29.1), and (f) daily pattern of fog collection (CWI_g) by a wire harp placed in the center of the study watershed (970 m.a.s.l.) between 10 July and 25, October 2001.

only three days did not have rain. Overall, 112 rainfall events were distinguished, with a mean duration of 10 hours, a mean size of 9.4 mm, and a mean intensity of ~0.7 mm hour^{-1} (Table 29.2). Median storm duration, size, and intensity were 8.5 hours, 5.2 mm, and ~0.4 mm hour^{-1}, respectively. Average rainfall after correction for the effect of slope (P_a, 11.3 mm day^{-1}) was 0.4 mm (4%) above measured rainfall (P, 10.9 mm day^{-1}, Table 29.2). Rainfall events were nearly always accompanied by fog; on average, fog occurred for 78% of the time during a rainfall event, and only nine out of the 112 events (8%) were completely fog-free.

Throughfall and stemflow

Between 10 July and 25 October 2001, the 67 totalizing *TF* gages were sampled 40 times. Mean *TF* per sampling occasion correlated well with P_a ($TF = 0.90P_a$, r2 = 0.98, n = 40). Cumulative *TF* per sampling position was divided by the corresponding P_a and multiplied by 100 to give relative throughfall (*TF/P*) at the 204 sampling positions (Figure 29.3a). The variation in point *TF* was considerable, ranging from 16% to 261% of P_a. Mean point *TF* was 90% of P_a, whereas median point *TF* was 83%; the standard deviation of the distribution shown in Figure 29.3a is 45%. Values of *TF* exceeded P_a in 57 out of 204 cases (28%). The coefficient of variation (CV, %) of mean *TF* per sampling occasion increased with decreasing P_a (Figure 29.3b). The highest CVs (>100%) were observed for P_a < 10 mm. In the

Table 29.1 *Statistical parameters of 64 fog* (CWI_g) *events, as measured with a wire harp between 10 July and 25 October 2001 at the Pico del Oeste watershed site, Puerto Rico*

Fog intercepted by the wire harp (CWI_g)	9.0 mm day^{-1} (n = 100, range: 0–26.6 mm day^{-1})
No. of fog events	64
Mean duration of fog event	27 hours (range: 1–188 hours)
Mean fog intercepted per event	14.1 mm (range: 0.0–134.5 mm)

Table 29.2 *Statistical parameters of 112 rainfall* (P) *events between 10 July and 25 October 2001 at the Pico del Oeste watershed site, and summarized corrections for the effect of slope. Mean daily amounts of throughfall* (TF) *and stemflow* (SF) *added for comparison*

Mean measured rainfall (P)	10.9 mm day^{-1} (n = 97; range: 0–76 mm day^{-1})
No. of rainfall events	112
Mean duration of rainfall event	10 hours (range: 1–43 hours)
Mean rainfall depth per event	9.4 mm (range: 0.1–77.1 mm)
Mean rainfall intensity (R)	0.7 mm hour^{-1} (range: 0.0–6.3 mm hour^{-1})
Mean slope correction factor	1.04 (range: 0.99–1.07)
Mean rainfall after slope correction (P_a)	11.3 mm day^{-1}
Throughfall (TF)	10.2 mm day^{-1} (n = 97, 90% of P_a)
Stemflow (SF)	0.6 mm day^{-1} (n = 97, 5% of P_a)

range P_a = 10–50 mm, the CV generally varied between 50% and 100%, whereas for P_a > 50 mm, it was generally between 50% and 60%. Mean *TF* for the 97 days with available rainfall data was 10.2 mm day^{-1}, corresponding to 90% of P_a (Table 29.2). Mean stemflow (*SF*) calculated using the fixed fraction of 0.05 was 0.6 mm day^{-1}. The mean sum of mean *TF* and *SF* (i.e. net precipitation P_{net}) was 10.8 mm day^{-1}, corresponding to 95% of P_a.

Modeled rainfall interception loss

Regressing *TF* against P_a for nine events with P_a < 1 mm and negligible fog (F_g < 0.2 mm) yielded a value for the free *TF* coefficient (p) of 0.23 (Figure 29.4a). Fitting a line of slope 0.95 ($1 - p_t$) through the upper points of the *TF* vs. P_a graph for eight storms with P_a > 1.5 mm and F_g < 0.5 mm gave an estimated canopy saturation value (S) of 0.50 mm, whereas the directly fitted line suggested a value of 0.46 mm (Figure 29.4b).

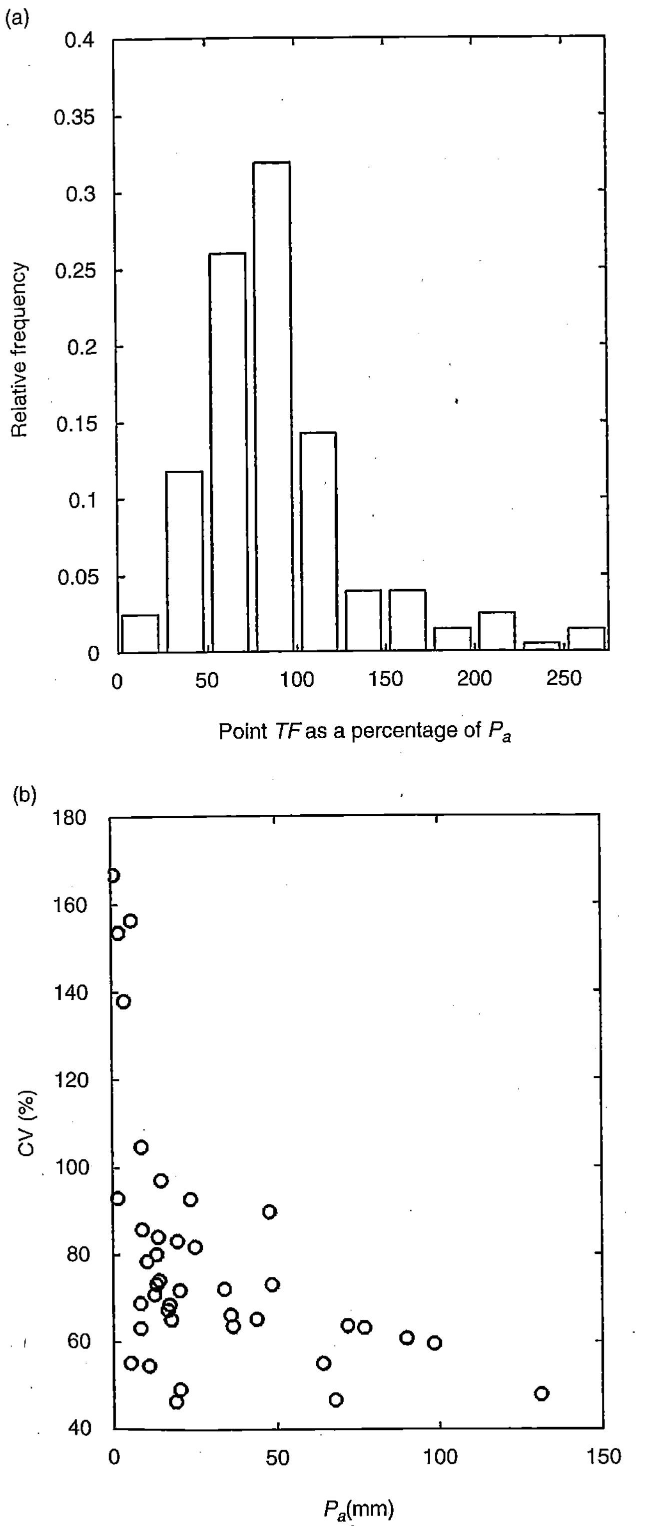

Figure 29.3. (a) Frequency distribution of point throughfall (*TF*) expressed as a percentage of corrected rainfall (P_a) at 204 sampling positions in the Pico del Oeste elfin cloud forest between 10 July and 25 October 2001. (b) Relationship between P_a and the coefficient of variation CV (100 × SD/mean) of mean *TF* for 40 sampling intervals (using 67 gages) for the same period.

The mean wet-canopy evaporation rate ($\overline{E_w}$) calculated for all hours with rainfall intensity $R_a \geq 0.50$ mm hour^{-1} was 0.06 mm hour^{-1}. The corresponding mean rainfall intensity $\overline{R_a}$ was 3.50 mm hour^{-1}, yielding the very low mean relative evaporation rate $\overline{E_w}/\overline{R_a}$ of 0.02 and model calculations were performed using this value. The mean amount of rainfall necessary to saturate the canopy P_a' (Gash, 1979) was 0.70 mm, and slightly higher than S (0.50 mm). Components of overall interception loss E_i as calculated with the analytical model for the 112 rainfall events were as follows: evaporation from the wetted canopy contributed only 28% (18.4 mm) of the total calculated E_i of 66.5 mm, the bulk of which (65%, or 43 mm) was associated with drying up of the canopy in between storms. Wetting up of the canopy contributed the remaining 8% (5.1 mm). Total calculated E_i was 6% of P_a (1099 mm).

Fog interception

The 112 rainfall (P_a) events of the study period gave as many (potential) estimates of fog interception (CWI_{wb}) based on the wet-canopy water budget equation. However, events for which the calculated error of CWI_{wb} ($SE_{CWI_{wb}}$) exceeded the estimate itself ($n = 30$), or for which the resulting CWI_{wb} value was negative ($n = 45$) were left out of the analysis (Table 29.3). The remaining 37 events (33%) that passed these selection criteria received less P_a (mean 4.6 mm event^{-1}) than fog (CWI_g as measured by the wire harp; mean 9.3 mm event^{-1}), while events with $SE_{CWI_{wb}} > CWI_{wb}$ had comparable amounts of P_a (mean 6.5 mm event^{-1}) and CWI_g (mean 6.4 mm event^{-1}). Events for which CWI_{wb} was negative, had much greater P_a (mean 16.3 mm) than CWI_g (mean 4.9 mm) (Table 29.3).

Mean measured event rainfall (P) for the 37 events that passed the criteria was 4.4 mm (not shown), whereas mean corrected event rainfall (P_a) was 5% higher (4.6 mm, Table 29.3). Mean event duration was about 14 hours, and mean fog occurrence was nearly 100%. Mean P_{net} ($TF + SF$, 5.7 mm) was about 24% higher than P_a. The estimated mean fog interception per event (CWI_{wb}) was 1.6 ± 0.8 mm. *CWI* rates (mm hour^{-1}) were estimated by dividing event CWI_{wb} by event duration, and these rates are plotted against corresponding collection rates CWI_g by the wire harp in Figure 29.5a. Despite considerable variation, estimated CWI_{wb} rates correlated significantly (at the 0.01 level) with CWI_g. The slope of the regression of CWI_{wb} against CWI_g (0.16, Figure 29.5a) can be taken to represent a "gage-to-canopy" conversion factor, which theoretically integrates differences in the fog-catching efficiencies of the wire harp and the forest canopy (Schellekens *et al.*, 1998; cf. García-Santos, 2007). Applying the latter factor to the record of the wire harp would suggest an average fog interception of about 1.4 mm day^{-1} (range: 0.0–4.2 mm day^{-1}, $n = 100$).

Table 29.3 *Summary of wet-canopy water budget components for rainfall* (P_a) *events for which (i) the calculated standard error in fog interception* ($SE_{CWI_{wb}}$*, Eq. 29.2) was larger than the estimate itself* (n = *30); (ii)* CWI_{wb} *was negative* (n = *45), or (iii)* CWI_{wb} *was positive and larger than* $SE_{CWI_{wb}}$ (n = *37) between 10 July and 25 October 2001 at the Pico del Oeste watershed site*

Event category	No. of events	Duration (hours)	Fog occurrence (%)	CWI_g (mm)	P_a (± SE) (mm)	TF (± SE) (mm)	SF (± SE) (mm)	E_i (± SE) (mm)	CWI_{wb} (± SE) (mm)
$SE_{CWI_{wb}} > CWI_{wb}$	30	13	68	6.4	6.5 (± 0.4)	6.1 (± 0.5)	0.3 (± 0.3)	0.5 (± 0.5)	0.4 (± 0.9)
$CWI_{wb}<0$	45	12	71	4.9	16.3 (± 0.8)	13.2 (± 1.0)	0.8 (± 0.8)	0.8 (± 0.8)	−1.5 (± 1.7)
$SE_{CWI_{wb}} < CWI_{wb}$ and $CWI_{wb} > 0$	37	14	95	9.3	4.6 (± 0.3)	5.5 (± 0.5)	0.2 (± 0.2)	0.5 (± 0.5)	1.6 (± 0.8)

Throughfall-based fog interception during fog-only periods (CWI_{tf}, excluding the first 3 hours after rainfall) were summed per fog event, yielding 37 estimates of CWI_{tf}. Estimated hourly rates correlated significantly (at the 0.01 level) with CWI_g (Figure 29.5b). The slope of the regression (0.12) again represents a gage-to-canopy conversion factor; applying the latter to the record of the wire harp yielded an average fog interception of about 1.1 mm day^{-1} (range: 0.0–3.3 mm day^{-1}, n = 100), i.e. slightly smaller than the water-budget based estimate (Figure 29.5a).

DISCUSSION

Rainfall

The presently measured mean daily rainfall (P) of 11 mm (Table 29.2) is close to the (long-term) value of 120–13 mm for nearby Pico del Este (García-Martinó *et al.*, 1996). Rainfall incident to the sloping canopy (P_a) was calculated from P using a trigonometric model. In doing so, it was assumed that the proportion of direct TF (p) was negligibly small. Arguably, direct TF would need to be corrected in a similar manner as rainfall (i.e. plus ~4%, Table 29.2) but this would increase the mean water-budget-based fog interception estimate (CWI_{wb}) by only 20–3%. The use of mean rainfall intensities and wind speeds per event in the model calculations introduced further simplifications. In reality, rainfall intensity, wind speed, and the angle of incidence of rain drops varied during events. In mountainous terrain, winds are greatly influenced by local topography; therefore, an unknown additional error was introduced by using the mean of the wind conditions as measured at the palm and cloud forest sites.

The mean correction factor for slope effects (+4%, Table 29.2) was much lower than that calculated by Holwerda *et al.* (2006a) for nearby Pico del Este (+28%). However, the Pico del Este site was not only windier (mean wind speed 50–6 m s^{-1}; Holwerda *et al.*, 2006a) than the present site (~3 m s^{-1}, Figure 29.2c), but it was also located on a steeper slope (17° vs. the present 11°). Furthermore, rainfall measurements at Pico del Este were made higher above the ground (1.8 m vs. 0.3 m in the present study), and storms had lower intensity (mean 0.4 mm hour^{-1} vs. the present 0.7 mm hour^{-1}, Table 29.2). García-Santos (2007) derived slope correction values of 130–18% for an exposed ridge-top site on La Gomera (Canary Islands) for average wind speeds of *c.* 3 m s^{-1}.

Fog occurrence

Fog occurred on average for 73% of the time according to the wire harp. This is somewhat lower than the values obtained by Holwerda *et al.* (2006a) and Baynton (1968) for nearby Pico del Este and Pico del Oeste (85% and 80% of the time, respectively). The difference may reflect the lower elevation at which the present study was conducted (i.e. 970 m.a.s.l. vs. 1010–1020 m.a.s.l.). Differences in measured fog occurrence may also relate to the use of different types of fog gages (Holwerda *et al.*, this volume #28). The present study and Baynton (1968) used passive fog gages (wire harp and louvered screen gage, respectively), whereas Holwerda *et al.* (2006a) measured fog occurrence directly with a Present Weather Detector.

Throughfall

Throughfall (TF) was spatially highly variable (Figures 29.3a and 29.3b); the distribution of point TF (expressed as a percentage of P_a) was positively skewed and ranged from 160% to 261%. Further, at 57 of the 204 sampling positions (28%) cumulative TF exceeded P_a (Figure 29.3a). Measuring TF at 80 sampling positions during 6 weeks in a similar, 3-m tall elfin cloud forest at nearby Pico del Este (using 20 roving gages), Holwerda *et al.* (2006a) found that at 34 of the 80 positions (43%) TF exceeded P_a. The distribution shown in Figure 29.3a has a mean relative TF and SD of 90% and 45% (of P_a), respectively, and

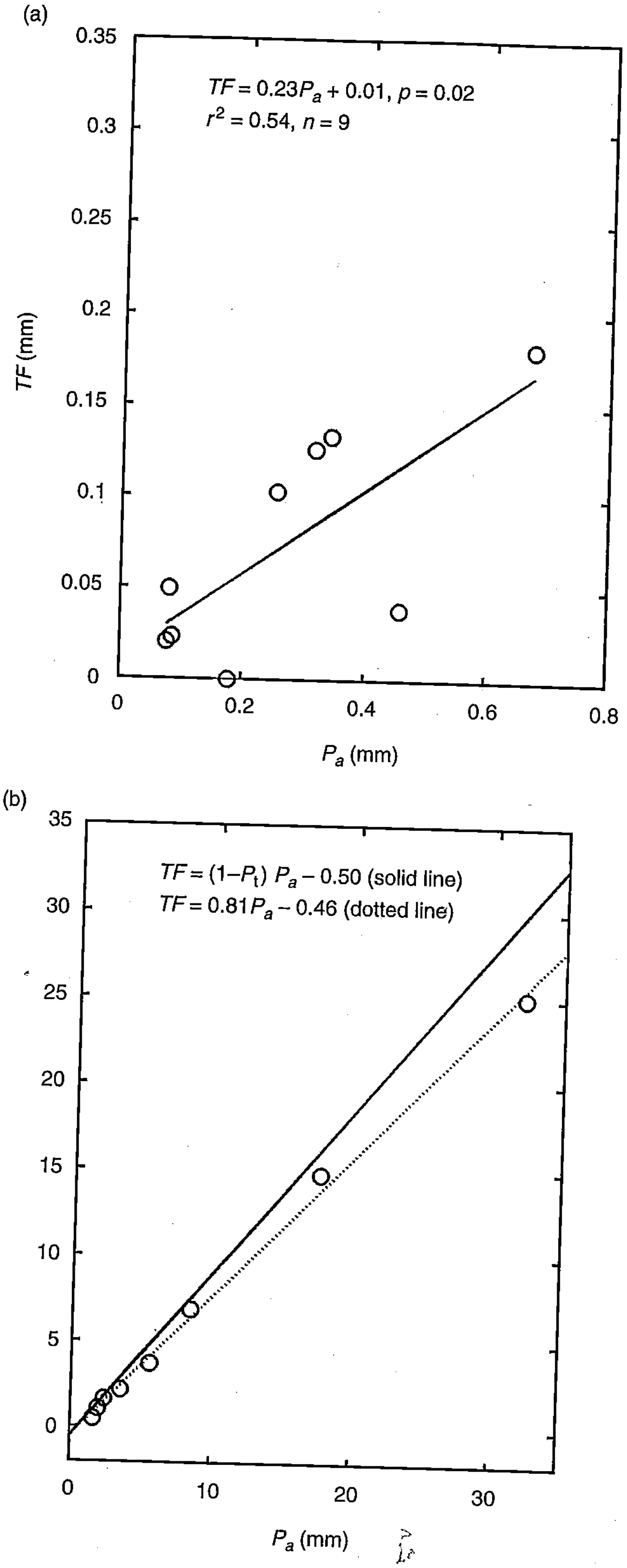

Figure 29.4. (a) Derivation of the direct throughfall coefficient (p, 0.23) at the Pico del Oeste watershed site following Jackson (1975). (b) Estimation of the canopy saturation value (S, 0.50 mm) by the method of Leyton *et al.* (1967). Stemflow fraction (p_t) taken as 0.05; the dotted line represents the best fit to the TF–P_a data pairs.

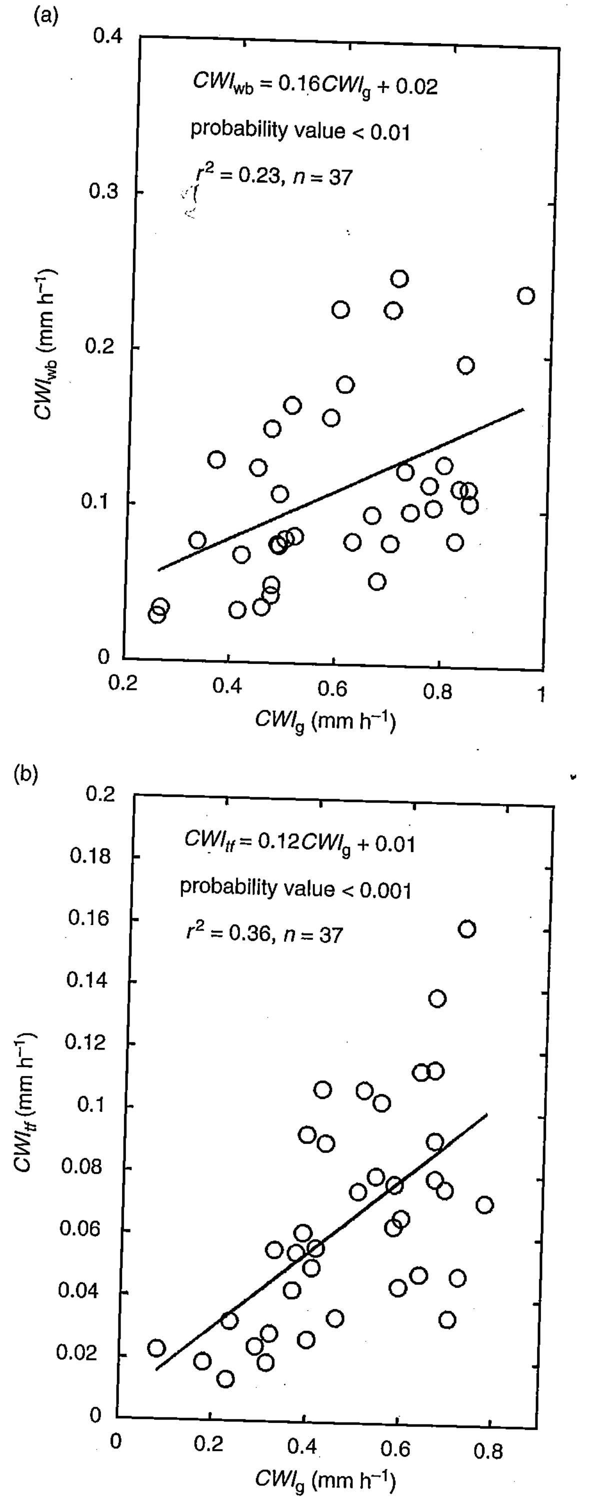

Figure 29.5. (a) Relationship between fog collection rates as measured by the wire harp (CWI_g, mm hour^{-1}) and water-budget-based fog interception rates (CWI_{wb}, mm hour^{-1}) for 37 rainfall (P_a) events between 10 July and 25 October 2001 at the Pico del Oeste watershed site. (b) Relationship between CWI_g and throughfall-based fog interception rates (CWI_{tf}, mm hour^{-1}) for 37 fog events during the same period.

hence, a CV of about 50%. Similar variability (about 48%) was observed by Holwerda *et al.* (2006b) between 160 point measurements of *TF* (March–November 2001, using 30 roving gages) in 20-m tall lower montane forest at 340 m a.s.l. The present result also compares well with the findings of Lloyd and Marques (1988) for lowland Amazonian rain forest (CV 500–55%). Although elfin cloud forest differs from lower montane and lowland rain forests in that the trees are much smaller and species diversity is considerably lower, the high variability of *TF* in the present forest may well be related to the presence of numerous, twisted branches covered with mosses and epiphytes (Weaver, 1995) and has consequences for the number of gages used (cf. Hafkenscheid *et al.*, 2002; Prada *et al.*, 2009).

Rainfall interception loss

Rainfall interception loss (E_i) was calculated using the analytical model of Gash (1979). One important assumption in the model is that the rainfall pattern can be represented by a series of discrete storms, separated by sufficiently long intervals for the canopy to dry completely. In the present study, storms were considered separate if preceded by at least 3 hours without rain. Continued fog interception, however, may have prevented the vegetation from drying up completely during such periods. In addition, the model results can only be compared with measured values of E_i for storms without fog, the number of which was small (only nine out of 112 storms).

The value for the canopy saturation value S (0.50 mm, Figure 29.4b) compares well with values reported for the elfin cloud forest at nearby Pico del Este (0.400–0.50 mm; Wickel, 1997; Holwerda *et al.*, this volume #28). A value of 0.50 mm would seem rather low considering the abundance of mosses and other epiphytes. Mosses are potentially capable of storing amounts of water that exceed several times their own dry weight (Weaver, 1972; Veneklaas *et al.*, 1990; Köhler *et al.*, 2007; Köhler *et al.*, this volume; Tobón *et al.*, this volume #26). However, because of the persistently wet conditions at the study site, it is very likely that the effective storage capacity of the mosses to absorb additional moisture was small (cf. Hölscher *et al.*, 2004; Köhler *et al.*, this volume). The value derived for the direct throughfall coefficient p (0.23, Figure 29.4a) is rather high considering the very high tree density (3671 stems ha^{-1} for trees with diameter at breast height DBH $\geq$ 10 cm) and the heavy epiphyte and bryophyte load of the forest (Weaver, 1995). However, this value of p was based on an analysis of storms $<$ 1 mm, while the canopy saturation value was already estimated at 0.50 mm (Figures 29.4a and 29.4b). Therefore, it is possible that the derived p value includes some indirect *TF* occurring after canopy saturation. Removal of intercepted rain drops from the vegetation by wind may also have increased the value of p, whereas the possibility of drops splashing off the hard, leathery leaves cannot be excluded either (cf. Schellekens *et al.*, 2000).

The mean wet-canopy evaporation rate $\overline{E_w}$ – based on the Penman–Monteith equation for hours with (slope corrected) rainfall intensity $R_a \geq 0.50$ mm hour^{-1} – was 0.06 mm hour^{-1}, which is equivalent to ~40 W m^{-2}. The corresponding mean rainfall intensity $\overline{R_a}$ was 3.50 mm hour^{-1}, yielding the very low mean relative evaporation rate $\overline{E_w}/\overline{R_a}$ of 0.02. However, $\overline{E_w}/\overline{R_a}$ as derived from the slope of the regression between measured E_i and P_a (Gash, 1979) for storms with little fog ($P_a/CWI_g > 10$) yielded the much higher value of 0.09 ($E_i = 0.09P_a + 0.79$, $r^2 = 0.37$, $n = 13$), implying an evaporation rate of ~0.27 mm hour^{-1}. Using the Penman–Monteith-based rate of $\overline{E_w}$, the model underestimated "measured" E_i losses for storms in excess of 10 mm in particular. However, it is not likely that the difference between measured and observed E_i was caused by a systematic underestimation of *TF* in view of the large number of gages used. Rather, the use of a fixed value of 5% for stemflow (*SF*) may have been too low. In recent years, several studies have reported high *SF* values for stunted upper montane and elfin cloud forests, e.g. Hafkenscheid *et al.* (2002) in Jamaica (18% of P), McJannet *et al.* (2007) in northern Queensland (14% of P, 11% of P_a), and Kumaran (2008) in Peninsular Malaysia (30.5% of P). Measuring *SF* in rain forests is generally difficult due to the large variation within and between tree species (Levia and Frost, 2003). Additional error is introduced when converting measured volumes (liters) to areal estimates (mm) using projected areas of sample tree crowns or overall stem density (cf. Hafkenscheid *et al.*, 2002). Finally, Tóbon-Marin *et al.* (2000) found that the *SF* fraction in lowland Amazonian rain forest increased with storm size whereas McJannet *et al.* (2007) observed relative amounts of *SF* to be enhanced during rainfall events with fog in various montane forests in northern Queensland. Therefore, *SF* may well have been underestimated in the present study by using a fixed value of 5%. The difference between the regression-based estimate of $\overline{E_w}/\overline{R_a}$ (0.09) and that based on the Penman–Monteith equation (0.02) was 0.07. Adding this difference to the *SF* fraction of 0.05 suggests that *SF* may have accounted for 12% of rainfall. By comparison, Weaver (1972) estimated *SF* at about 10% of the rainfall for a ridge-top elfin forest at nearby Pico del Este.

Because of the low radiation inputs and high humidity levels (Figures 29.2a and 29.2e), the analytical model results suggest that evaporation from a saturated canopy contributed only 28% (18.4 mm) of total E_i (66.5 mm), with the bulk of E_i consisting of evaporation during drying of the canopy (43.0 mm, about 65%) after rainfall ceased. However, the frequently foggy conditions at the site may have invalidated the assumption of complete canopy drying between storms. To assess the (approximate) effect of incomplete canopy drying between storms on the water-budget-based fog gage to canopy conversion factor (0.16, Figure 29.5a), the (effective) canopy saturation value (S) was decreased from 0.50 to 0.25 mm. This had a comparatively small effect on the magnitude of the gage to canopy factor (0.15, i.e. −6%).

Fog interception

Solving the wet-canopy water budget (Eq. 29.1) for each of the 112 rainfall events (Table 29.2) yielded 37 estimates of fog interception (CWI_{wb}) that were both positive and larger than their error estimates $SE_{CWI_{wb}}$. However, for the majority of events, estimates of CWI_{wb} were either smaller than $SE_{CWI_{wb}}$ ($n = 30$) or even negative ($n = 45$) (Table 29.3). As discussed previously, the difference between modeled and observed interception loss (E_i) may have been caused by an underestimation of *SF*. For the same reason, estimates of CWI_{wb} may become negative when solving the budget equation for large rainfalls. In addition, errors in the individual water budget terms became large compared to the magnitude of CWI_{wb} whenever P_a exceeded the catch of the wire harp (CWI_g). This also applied to events with comparable amounts of P_a and CWI_g. Thus, solving the wet-canopy water budget for CWI_{wb} gave the best results when P_a was small compared to CWI_g (Table 29.3).

Although the variation in estimates of CWI_{wb} was large due to accumulation of errors in individual water budget terms (Table 29.3), estimated fog interception correlated significantly with collection rates by the wire harp (Figure 29.5a). Also, throughfall-based fog interception rates (CWI_{tf}) during periods with fog-only correlated slightly better with CWI_g (Figure 29.5b), probably because the error in CWI_{tf} was determined solely by variation in *TF*. The gage to canopy conversion factor based on CWI_{tf} (0.12, Figure 29.5b) was somewhat lower than that based on CWI_{wb} (0.16, Figure 29.5a), probably because both *SF* and E_i were neglected in the calculations of CWI_{tf}. However, considering the wide error bands associated with CWI_{wb} (Table 29.3), this difference may also reflect the error in CWI_{wb}.

Applying the gage-to-canopy conversion factors to the record of the wire harp suggested a fog interception rate of 1.10–1.4 mm day^{-1}, equivalent to 10–12% of mean P_a. Interestingly, the presently derived estimate is 30–50% lower than the 2.1 mm day^{-1} value derived by Holwerda *et al.* (2006a) for very similar forest at nearby Pico del Este. This difference is thought to largely reflect contrasts in site exposure. The Pico del Este site was located just below a ridge top and more exposed to winds than the present site.

CONCLUSIONS

Fog interception (*CWI*) by a Puerto Rican elfin cloud forest at 970 m.a.s.l. was studied between 10 July and 25 October 2001. Fog, as indicated by a shielded wire harp, occurred on average for 73% of the time (55% during the day and 89% at night). Mean daily *CWI* rates as estimated from the wet-canopy water budget (1.4 mm) and from throughfall measurements during periods with fog-only (1.1 mm) were 12% and 10% of mean corrected daily rainfall (11.3 mm), respectively. At 1.1–1.4 mm day^{-1}, *CWI* was 30–50% lower than the water-budget-based estimate of 2.1 mm day^{-1} for a similar, but more exposed elfin cloud forest in the same area.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W76–206). The authors thank C. Estrada, G. Guzman, S. Moya, and C. Torrens (U.S. Department of Agriculture Forest Service) for their help during the field work and Dr. Werner Eugster for helpful comments on an earlier draft.

REFERENCES

Baynton, H. W. (1968). Ecology of an elfin forest in Puerto Rico. II. Microclimate of Pico Del Oeste. *Journal of the Arnold Arboretum* **49**: 419–430.
Blocken, B., J. Carmeliet, and J. Poesen (2005). Numerical simulation of the wind-driven rainfall distribution over small-scale topography in space and time. *Journal of Hydrology* **315**: 252–273.
Brown, S., A. E. Lugo, S. Silander, and L. Liegel (1983). *Research History and Opportunities in the Luquillo Experimental Forest.* New Orleans, LA: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station.
Bruijnzeel, L. A. (2005). Tropical montane cloud forests: a unique hydrological case. In *Forests, Water and People in the Humid Tropics*, eds. M. Bonell and L. A. Bruijnzeel, pp. 462–483. Cambridge, UK: Cambridge University Press.
Cavelier, J., D. Solis, and M. A. Jaramillo (1996). Fog interception in montane forests across the Central Cordillera of Panama. *Journal of Tropical Ecology* **12**: 357–369.
Frumau, K. F. A., L. A. Bruijnzeel, and C. Tobón (2006). Measurement of precipitation in montane tropical catchments: comparative performance of conventional, spherical and "potential" rain gages. In *Forest and Water in a Changing Environment*, eds. S. R. Liu, G. Sun, and P. S. Sun, pp. 104–108. Vienna: IUFRO, and Beijing: Chinese Academy of Forestry.
García-Martinó, A. R., G. S. Warner, F. N. Scatena, and D. L. Civco (1996). Rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico. *Caribbean Journal of Science* **32**: 413–424.
García-Santos, G. (2007). *An ecohydrological and soils study in a montane cloud forest in the National Pak of Garajonay, La Gomera (Canary Islands, Spain).* Ph.D. thesis VU University, Amsterdam, the Netherlands. Also available at www.falw.vu.nl/nl/onderzoek/earth-sciences/geo-environmental-science-and-hydrology/hydrology-dissertations/index.asp.
Gash, J. H. C. (1979). An analytical model of rainfall interception by forests. *Quarterly Journal of the Royal Meteorological Society* **105**: 43–55.
Goodman, J. (1985). The collection of fog drip. *Water Resources Research* **21**: 392–394.
Hafkenscheid, R. L. L. J., L. A. Bruijnzeel, R. A. M. de Jeu, and N. J. Bink (2002). Water budgets of two upper montane rain forests of contrasting stature in the Blue Mountains, Jamaica. In *Proceedings of the 2nd International Colloquium on Hydrology and Water Management in the Humid Tropics*, Technical Documents in Hydrology No. **52**, ed. J. S. Gladwell, pp. 399–424. Paris: IHP–UNESCO.

Harr, R. D. (1982). Fog-drip in the Bull Run municipal watershed, Oregon. *Water Resources Bulletin* **18**: 785–789.
Holder, C. D. (2003). Fog precipitation in the Sierra de las Minas Biosphere Reserve, Guatemala. *Hydrological Processes* **17**: 2001–2010.
Hölscher, D., L. Köhler, A. I. J. M. Van Dijk, and L. A. Bruijnzeel (2004). The importance of epiphytes to total rainfall interception by a tropical montane rain forest in Costa Rica. *Journal of Hydrology* **292**: 308–322.
Holwerda, F. (2005). Water and energy budgets of rain forests along an elevation gradient under maritime tropical conditions. Ph.D. thesis VU University, Amsterdam, the Netherlands. Also available at www.falw.vu.nl/nl/onderzoek/earth-sciences/geo-environmental-science-and-hydrology/hydrology-dissertations/index.asp.
Holwerda, F., R. Burkard, W. E. Eugster, *et al.* (2006a). Estimating fog deposition at a Puerto Rican elfin cloud forest site: comparison of the water budget and eddy covariance methods. *Hydrological Processes* **20**: 2669–2692.
Holwerda, F., F. N. Scatena, and L. A. Bruijnzeel (2006b). Throughfall in a Puerto Rican lower montane rain forest: a comparison of sampling strategies. *Journal of Hydrology* **327**: 592–602.
Jackson, I. J. (1975). Relationships between rainfall parameters and interception by tropical forest. *Journal of Hydrology* **24**: 215–238.
Juvik, J. O. and P. C. Ekern (1978). *A Climatology of Mountain Fog on Mauna Loa, Hawai'i Island*, Technical Report No. 118. Honolulu, HI: Water Resources Research Center, University of Hawai'i.
Köhler, L., C. Tobón, K. F. A. Fruman, and L. A. Bruijnzeel (2007). Biomass and water storage of epiphytes in old-growth and secondary montane rain forest stands in Costa Rica. *Plant Ecology* **193**: 171–184.
Kumaran, S., (2008). Hydrometeorology of Tropical montane rain forests of Gunung Brinchang, Pahang Darul Makmur, Malaysia. Ph.D. thesis, University Putra Malaysia, Serdang, Malaysia.
Levia, D. R. Jr., and E. E. Frost (2003). A review and evaluation of stemflow literature in the hydrological and biogeochemical cycles of forested and agricultural ecosystems. *Journal of Hydrology* **274**: 1–29.
Leyton, L., E. R. C. Reynolds, and F. B. Thompson (1967). Rainfall interception in forest and moorland. In *International Symposium on Forest Hydrology*, eds. W. E. Sopper and H. W. Lull, pp. 163–168. Oxford, UK: Pergamon Press.
Lloyd, C. R., and A. O. Marques Filho (1988). Spatial variability of throughfall and stemflow measurements in Amazonian rain forest. *Agriculture and Forest Meteorology* **42**: 63–73.
McJannet, D., J. Wallace, and P. Reddell (2007). Precipitation interception in Australian tropical rainforests. II. Altitudinal gradients of cloud interception, stemflow, throughfall and interception. *Hydrological Processes* **21**: 1703–1718.
Monteith, J. L. (1965). Evaporation and the environment. *Symposia of the Society for Experimental Biology* **19**: 245–269.
Mulligan, M., and S. M. Burke (2005). *DFID FRP Project R7991, FIESTA: Fog Interception for the Enhancement of Streamflow in Tropical Areas*, Final Technical Report of AMBIOTEK/King's College London contributions. Leigh-on-Sea, UK: AMBIOTEK. Also available at www.ambiotek.com/fiesta.
Mulligan, M., K. F. A. Frumau, and L. A. Bruijnzeel (2006). Falling at the first hurdle: spatial rainfall variability and the problem of closing catchment water budgets in tropical montane environments. In *Forest and Water in a Changing Environment*, eds. S. R. Liu, G. Sun, and P. S. Sun, pp. 114–117. Vienna: IUFRO, and Beijing: Chinese Academy of Forestry.
Prada, S., M. Menezes de Sequeiro, C. Figueira, and M. Oliveira da Silva (2009). Fog precipitation and rainfall interception in the natural forests of Madeira Island (Portugal). *Agricultural and Forest Meteorology* **149**: 1179–1187.
Schellekens, J., L. A. Bruijnzeel, A. J. Wickel, F. N. Scatena, and W. L. Silver (1998). Interception of horizontal precipitation by elfin cloud forest in the Luquillo Mountains, eastern Puerto Rico. In *Proceedings of the 1st International Conference on Fog and Fog Collection*, eds. R. S. Schemenauer and H. A. Bridgman, pp. 29–32. Ottawa, Canada: IDRC.
Schellekens, J., L. A. Bruijnzeel, F. N. Scatena, N. J. Bink, and F. Holwerda (2000). Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. *Water Resources Research* **36**: 2183–2196.
Sevruk, B. (1982). *Methods of Correction for Systematic Error in Point Precipitation Measurement*. Geneva, Switzerland: World Meteorological Organization.
Sharon, D. (1980). Distribution of hydrologically effective rainfall incident on sloping ground. *Journal of Hydrology* **46**: 165–188.
Stadtmüller, T., and N. Agudelo (1990). Amount and variability of cloud moisture input in a tropical cloud forest. *International Association of Hydrological Sciences Publication* **193**: 25–32.
Tóbon-Marin, C., W. Bouten, and J. Sevink (2000). Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four ecosystems in western Amazonia. *Journal of Hydrology* **237**: 40–57.
Veneklaas, E. J., R. J. Zagt, A. van Leerdam, *et al.* (1990). Hydrological properties of the epiphyte mass of a montane tropical rain forest, Colombia. *Vegetatio* **89**: 183–192.
Walmsley, J. L., R. S. Schemenauer, and H. A. Bridgman (1996). A method for estimating the hydrological input from fog in mountainous terrain. *Journal of Applied Meteorology* **35**: 2237–2249.
Weaver, P. L. (1972). Cloud moisture interception in the Luquillo Mountains in Puerto Rico. *Caribbean Journal of Science* **12**: 129–144.
Weaver, P. L. (1995). The colorado and dwarf forests of Puerto Rico's Luquillo Mountains. In *Tropical Forests: Management and Ecology*, eds. A. E. Lugo and C. Lowe, pp. 109–141. New York: Springer-Verlag.
Wickel, A. J. (1997). Rainfall interception modelling for two tropical forest types in the Luquillo Experimental Forest, *Puerto Rico*. M.Sc. thesis, VU University, Amsterdam, the Netherlands.
Zadroga, F. (1981). The hydrological importance of a montane cloud forest area of Costa Rica. In *Tropical Agricultural Hydrology*, eds. R. Lal and E. W. Russell, pp. 59–73. New York: John Wiley.