28 Comparison of passive fog gages for determining fog duration and fog interception by a Puerto Rican elfin cloud forest

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

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

ABSTRACT

Between 5 March and 10 May 2001, the performance of three types of passive fog gages (wire harp *WH*, standard fog collector *SC*, and Juvik gage *JU*) was compared at a wind-exposed Puerto Rican elfin cloud forest site. The gages were used to determine the timing and duration of fog and of fog-induced crown drip. Gage to canopy conversion factors were derived from the ratio between throughfall, and fog collected by the respective gages during periods with fog-only and negligible evaporation loss. The fog gages indicated very similar timing and fog duration, presumably because dense fog prevailed for 75–80% of the time and winds were generally sufficiently strong (4–5 m s^{-1}). Resulting gage-to-canopy factors were 0.12 for *WH* and *SC*, and 0.10 for *JU*. Estimating fog interception by the canopy using these conversion factors gave very similar values for the three gage types (mean rates of 0.15 ± 0.01 mm $hour^{-1}$). Throughfall typically started about 5 hours after the fog gages indicated the beginning of a fog event. This time lag probably reflects the filling of the storage capacity of the canopy, because wet canopy evaporation was negligible. Integrating the estimated fog interception rates over the time lag suggested an average value of 0.4 mm for the canopy storage capacity during events with fog-only.

INTRODUCTION

Rates and amounts of fog interception by vegetation depend on wind speed, fog liquid water content (*LWC*) and duration, as well as surface area and geometry of the vegetation (Schemenauer, 1986). Information on the timing and duration of fog can be obtained with passive fog gages, provided these are protected from rainfall and equipped with a recording device (Bruijnzeel *et al.*, 2005). Fog *LWC* may also be evaluated from collections by passive gages when information on their collection efficiency and prevailing wind speeds is available (e.g. Schemenauer and Joe, 1989). A variety of passive gages is available, and there has been some discussion as to what is the most suitable type of gage to characterize local fog conditions (Juvik and Nullet, 1995a; Schemenauer and Cereceda, 1995; cf. Delay and Giambelluca, this volume; Frumau *et al.*, this volume). For example, a cylindrical gage is considered superior to a flat screen, because it has uniform exposure to all wind directions (Juvik and Nullet, 1995a; cf. García Santos, 2007; Giambelluca *et al.*, this volume). On the other hand, a flat screen generally has a much larger collection area than a cylindrical gage, and may thus measure fog when *LWC* or wind speeds are low (Schemenauer and Cereceda, 1995).

Amounts of fog water collected by a fog gage are not necessarily representative of those actually intercepted by a forest canopy. However, good relationships have been found between collection rates of passive gages and fog-induced throughfall, *TF* (Joslin *et al.*, 1990; Vong *et al.*, 1991; Juvik and Nullet, 1995b;

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.

Holwerda *et al.*, this volume #29). Dividing amounts of fog-induced *TF* by the corresponding volumes collected by a fog gage yields a so-called gage-to-canopy conversion factor, which theoretically integrates the difference in fog-catching efficiency between gage and canopy (Schellekens *et al.*, 1998). This factor may then be used to estimate fog interception from the fog gage record over an extended period.

This paper reports on a comparison of three types of passive fog gages (wire harp *WH*, "standard" fog collector *SC*, and cylindrical aluminum louvered screen *JU*) as used between 5 March and 10 May 2001 at a wind-exposed elfin cloud forest site near Pico del Este, Puerto Rico. The fog gages were equipped with a tipping bucket and data-logging system to obtain continuous records. Throughfall and above-canopy climatic parameters (including wind speed and wind direction) were measured as well. The following questions were addressed: (i) what is the most suitable type of gage to characterize fog conditions (timing, duration, intensity) at wind-exposed sites such as Pico del Este?; (ii) how do estimates of fog interception based on gage to canopy factors differ between the three types of gages?; and (iii) how does the timing of canopy drip relate to fog occurrence according to the respective gages?

STUDY AREA

The study site was located at *c.* 1010 m.a.s.l. near Pico del Este (1052 m.a.s.l.), the easternmost summit in the Luquillo Mountains, Puerto Rico. Fog measurements were made at a local ridge top whereas additional climatic and *TF* measurements were made about 30 m below the ridge top on a 17° slope facing N40E. The prevailing trade winds blow mainly from the east, and wind speeds are typically 4–5 m s^{-1} with little seasonal variation (Briscoe, 1966; Brown *et al.*, 1983). Mean annual rainfall at Pico del Este is 4435 mm $year^{-1}$. On average, most rainfall occurs during the months of 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 relative humidity below the forest canopy at Pico del Este is close to saturation (99.7%; Weaver, 1972). Fog occurs for about 60–75% of the time during the day and for about 95–100% of the time at night (Baynton, 1968; Holwerda *et al.*, 2006). Mean monthly temperatures range between 17 °C and 20 °C (Brown *et al.*, 1983). The vegetation at Pico del Este is typical of the elfin cloud forest type found on peaks and ridges above 900 m.a.s.l. in the Luquillo Mountains, and is dominated by *Tabebuia rigida*, *Ocotea spathulata*, and *Micropholis garcinaefolia* having a mean height of ~3 m. The forest is rich in epiphytes, with mosses and bromeliads covering branches, stems, and part of the soil surface (Weaver, 1995). Leaf area index, as estimated from light extinction measurements (F. Holwerda, unpublished data), was 2.1 ± 0.7, close to the value of 2.0 found by Weaver *et al.* (1986) for the same forest using destructive sampling methods.

METHODS

General climatic parameters

Above-canopy climatic measurements were made at a measuring interval of 30 s in a 7.5-m tall mast placed in a small, natural clearing. The measurements were recorded by a Campbell Scientific 21X data-logger that stored the averaged data every 5 min in an external storage module. Incoming and outgoing short- and long-wave radiation components were measured separately above the canopy with Kipp and Zonen albedometers and Eppley Pyrgeometers, respectively. Net radiation was determined by adding the respective components. Air temperature and relative humidity were measured with a combined sensor (Vaisala, HMP45C) housed in a ventilated radiation screen. Wind speed and direction were measured using an A100R switching anemometer (at 5 m) and a W200P potentiometer wind vane (at 7.4 m), respectively (Vector Instruments, UK). Rainfall was measured with a tipping bucket rain gage (Campbell Scientific Ltd., ARG100, 500 cm^2 orifice, 0.20 mm per tip) placed in a small clearing about 10 m from the mast. Evaporation from the wet canopy (E_w) was calculated from the above-canopy climatic data using the wet variant of the Penman–Monteith equation (Monteith, 1965).

Fog

Fog occurrence was measured using three types of passive gages: a wire harp *WH* (Goodman, 1985), a modification of the "standard" fog collector *SC* (Schemenauer and Cereceda, 1994), and a cylindrical aluminum louvered screen *JU* (Juvik and Ekern, 1978). Two gages of each type were installed next to each other on the ridge top with the center of their collection area at 2.5 m above the ground. The gages were freely exposed to the prevailing winds and not protected against rainfall. The *WH* consisted of a 0.5 × 0.5 m flat screen with 0.8 mm vertical nylon strings spaced 2 mm apart. To achieve better comparability with the *WH*, the dimensions of the *SC* were adjusted to 0.5 × 0.5 m instead of the 1.0 × 1.0 m proposed originally by Schemenauer and Cereceda (1994) (see also García-Santos and Bruijnzeel, this volume). The polypropylene mesh of the *SC* consists of a triangular weave of a flat fiber about 1 mm wide and 0.1 mm thick (Schemenauer and Cereceda, 1994). Both the *WH* and *SC* were positioned so as to face the easterly trade winds. The *JU* gage consists of a cylindrical aluminum louvered screen (13 cm in diameter by 40 cm in height) (see Juvik and Ekern, 1978 or Juvik and Nullet, 1995a for details). Tubing from each of the gages led into tipping bucket systems (5 ml per tip) connected to custom-built data-loggers (VU

University Amsterdam). Volumes of fog water collected by the gages (l) were converted to water depth equivalent (mm) by dividing by the collecting area of the respective gages (i.e. $0.25\ m^2$ for *WH* and *SC*, and $0.052\ m^2$ for *JU*).

Throughfall

Throughfall (*TF*) was measured with two large steel gutters (projected surface areas of 1.11 and $1.14\ m^2$) placed near the meteorological mast. Each gutter had a tipping bucket system (50 ml per tip) connected to a custom-built data-logger (VU University Amsterdam).

Derivation of fog gage to canopy conversion factors

For a fog-only event, the wet canopy water budget of a forest reads:

$$CWI = TF + SF + E_i \quad (28.1)$$

in which *CWI* is gross cloud water (fog) interception, *TF* throughfall, *SF* stemflow, and E_i evaporation from the wet canopy (interception loss); all components are expressed in mm of water per time period. Because *SF* during events with fog-only is probably negligible, it was not considered separately.

For saturated canopy conditions and negligible wet canopy evaporation rate (E_w), net fog interception (CWI_{net}) more or less equals *TF*. Dividing gross or net values of *CWI* by the amount of fog collected by a fog gage of type *x* (CWI_x) yields the corresponding gage to canopy conversion factor (f_x) (Schellekens *et al.*, 1998).

The simplified conditions under which *TF* equals (net) *CWI* were met by using all 30-min measuring intervals having $TF > 0.1$ mm and $E_w < 0.01$ mm. The first 3 hours after rainfall had ceased were excluded from the analysis to avoid any contributions by rain-induced *TF*.

RESULTS AND DISCUSSION

Comparison of fog collection rates by the different gages

After defining fog events as being separated by a fog-free period of at least 3 hours to ensure a fully dry canopy at the start of an event (Schellekens *et al.*, 1998) 40 events were extracted from the record for the period between 5 March and 10 May 2001. Mean event duration was about 34 hours. However, median duration was only about 19 hours because of the strongly positively skewed distribution of event durations. Comparisons between fog collection rates by the three types of gages were made using data from eight fog-only events (Figure 28.1). Collection rates by the *SC* and the *WH* were equal (Figure 28.1a) whereas those by the *JU* were 24% higher (Figure 28.1b). The *JU* showed a

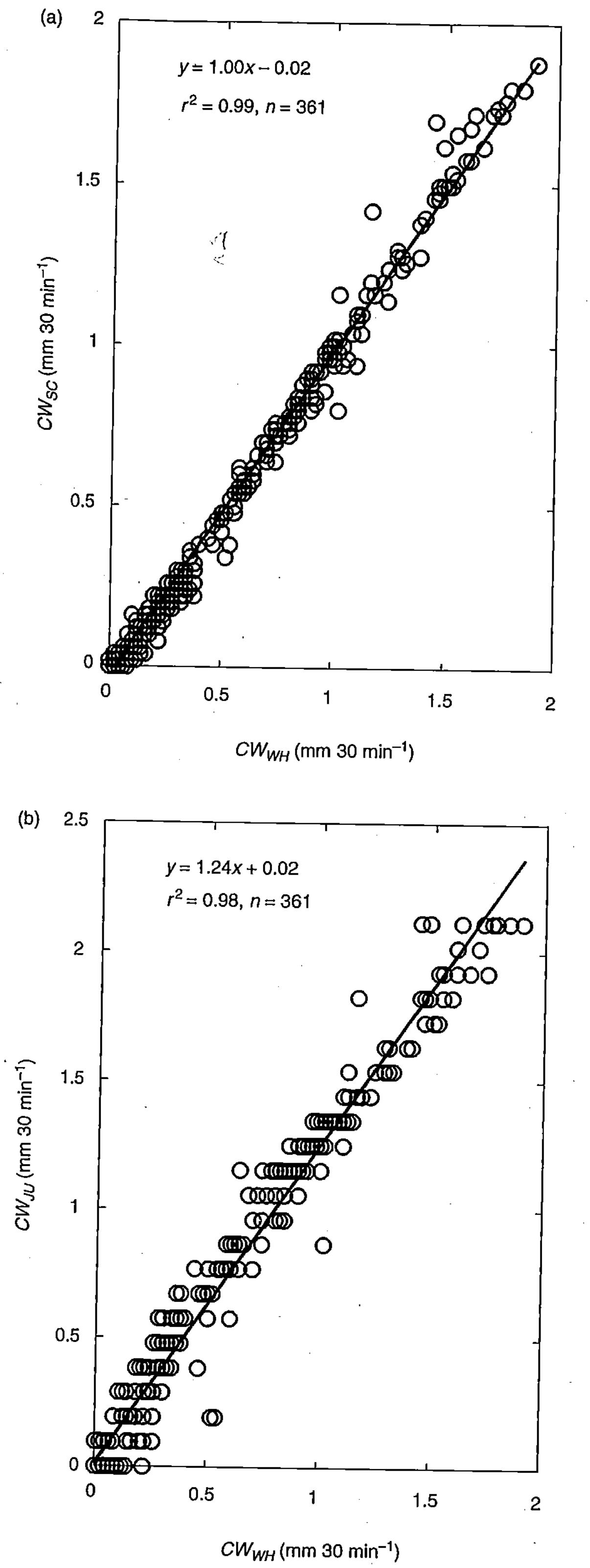

Figure 28.1. Relationships between fog collection rates (CWI_x, mm 30 min^{-1}) by (a) the wire harp *WH* and standard gauge *SC* and (b) *WH* and the Juvik gauge *JU* for eight fog-only events between 5 March and 10 May 2001 at Pico del Este.

Table 28.1 *Average gage-to-canopy factors* f_x *as derived for a wire harp* WH, *a modified standard fog collector* SC, *and a Juvik-type fog gage* JU *based on 120 30-min intervals with throughfall* TF > *0.1 mm and wet canopy evaporation* E_w < *0.01 mm between 5 March and 10 May 2001 at Pico del Este, Puerto Rico. Also shown are coefficients of variation CV of* f_x *and relationships between above-canopy wind speed* U *and* f_x

Fog gage type	f_x	CV (%)	n	Wind-dependency $f_x = aU + b$	r^2	p value
Wire harp (*WH*)	0.12	20	120	$f_x = 0.008U + 0.073$	0.10	<0.01
Modified standard collector (*SC*)	0.12	17	120	$f_x = 0.005U + 0.094$	0.05	0.01
Juvik-type (*JU*)	0.10	20	120	$f_x = 0.001U + 0.093$	0.00	0.68

slightly delayed response at times of low fog incidence, probably because of its smaller collection area.

Derivation of gage to canopy conversion factors

Gage-to-canopy conversion factors f_x were calculated using 120 30-min intervals with throughfall $TF > 0.1$ mm, wet canopy evaporation $E_w < 0.01$ mm, and excluding the first 3 hours after rainfall P had ceased (Table 28.1). Because *CWI* rates obtained with the *WH* and *SC* were equal, the corresponding conversion factors were also equal (0.12). Because of the higher collection rates of the *JU* (Figure 28.1), f_{JU} was slightly lower (Table 28.1; cf. Frumau *et al.*, this volume). The variability of f_x was very similar for the three types of gages (17–20%, Table 28.1). Whilst f_{WH} and f_{SC} were weakly but significantly correlated (at the 0.05 level) with wind speed (U), no such relationship was found for f_{JU} (Table 28.1). The strings of the harp started to vibrate at high values of U, causing already intercepted drops to fall off again and be blown away (cf. Frumau *et al.*, this volume). However, there was no relationship between f_{WH} and U when 30-min intervals with $U > 8$ m s^{-1} were excluded from the analysis. Because wind speeds greater than 8 m s^{-1} do not often occur at the study site (only for 2% of the time during the 9-week study period), effects of wind-dependency of f_{WH} on calculated *CWI* totals were unimportant. Neither was there a relationship between f_{SC} and U for $U < 8$ m s^{-1}. Conversely, f_{JU} showed no wind-dependency at high U, probably because its rigid aluminum screen is not easily shaken. It is unknown to what extent the calculated f_x values are also valid at very low wind speeds ($U < 2$ m s^{-1}). Under such conditions, gravitational settling rather than turbulent diffusion governs fog deposition on the forest canopy (Beswick *et al.*, 1991), and collection efficiencies of fog gages often drop under such conditions (Schemenauer and Joe, 1989). At the Pico del Este site, however, winds are typically 4–5 m s^{-1}, and they do not often fall below 2 m s^{-1} (14% of the time during the study period).

In addition, the collection efficiencies of the flat *WH* and *SC* depend on wind direction because of their fixed orientation, while the cylindrical *JU* offers uniform exposure to winds from all directions (Juvik and Nullet, 1995a; cf. Schemenauer and Cereceda, 1995). However, winds at Pico del Este came from easterly directions for 77% of the time during the study period, rendering effects of gage orientation on f_x relatively unimportant (cf. Giambelluca *et al.*, this volume). Conversely, wind direction effects on the catch of a similarly sized *SC* at an exposed ridge top in La Gomera (Canary Islands) appeared substantial (García-Santos, 2007).

Fog duration and interception

Eight events with fog-only occurring between 5 March and 10 May 2001 were analyzed in detail (Table 28.2). The *WH* and *SC* indicated almost equal event durations (means of 16 hours), while the *JU* gave somewhat lower values (mean of 15 hours, Table 28.2). The difference was most pronounced for event no. 31, when event duration was 6 hours according to the JU, vs. 13 and 12 hours according to the *WH* and *SC*, respectively (Table 28.2). However, the fog was very light at the start of this particular event (with collection rates by the *WH* < 0.1 mm 30 min^{-1}). Under such conditions, the collection area of the *JU* was probably too small to yield measurable amounts of fog (Figure 28.1). Between 25 June and 6 August 2002, Holwerda *et al.* (2006) measured visibility (*VIS*, m) at the same site using a Present Weather Detector. Dense fog (*VIS* < 250 m) occurred for about 77% of the time, while fog with *VIS* between 250 and 1000 m occurred for only about 8% of the time. Therefore, and because of the sufficiently strong winds prevailing at the site (4–5 m s^{-1}), the variability in event duration as indicated by the respective gage types was generally less than 5% (Table 28.2). The variability in estimates of event *CWI* by the forest as obtained by the use of the respective gage to canopy factors f_x, was generally small as well (≤10%, Table 28.2). Mean hourly net *CWI* rates were calculated for each gage type using all hours without rainfall and excluding the first 3 hours after rainfall had ceased. This gave values of 0.15 ± 0.10 mm hour^{-1} (SD) for the *WH*, 0.14 ± 0.11 mm hour^{-1} for the *SC*, and 0.15 ± 0.11 mm hour^{-1} for the *JU*. The presently found average rate of

Table 28.2 *Fog interception* (CWI_x*, mm) and event duration (hours) as indicated by a wire harp* WH, *a modified standard fog collector* SC, *and a Juvik-type gage* JU *for eight fog-only events between 5 March and 10 May 2001 at Pico del Este, Puerto Rico.* CWI *by the forest canopy based on the respective average gage-to-canopy factors* f_x. *Amounts of fog drip* (TF) *added for comparison*

Event	Duration (hours)					CWI_x (mm)			CWI (mm)					TF
	WH	*SC*	*JU*	Mean	CV (%)	*WH*	*SC*	*JU*	*WH*	*SC*	*JU*	Mean	CV (%)	(mm)
5	16	17	16	16	2	26.7	26.5	35.3	3.3	3.3	3.4	3.3	3	2.1
6	18	18	17	17	2	15.0	13.4	20.8	1.8	1.7	2.0	1.8	10	1.1
7	16	16	15	16	3	8.1	6.0	10.9	1.0	0.7	1.1	0.9	18	0.1
8	36	35	35	35	2	66.4	64.7	82.4	8.1	8.0	8.0	8.1	1	6.0
10	15	15	14	15	4	31.3	30.8	38.8	3.8	3.8	3.8	3.8	1	3.2
16	5	3	3	4	25	1.1	0.9	1.4	0.1	0.1	0.1	0.1	11	0.0
29	14	14	11	13	11	5.6	5.0	7.4	0.7	0.6	0.7	0.7	8	0.0
31	13	12	6	10	39	1.3	0.8	1.1	0.2	0.1	0.1	0.1	29	0.0
Mean	16	16	15	16	11	19.4	18.5	24.8	2.4	2.3	2.4	2.4	10	1.6

0.15 ± 0.11 mm hour^{-1} is slightly higher than the 0.11 ± 0.05 mm hour^{-1} derived for conditions of fog-only by Holwerda *et al.* (2006) for the same site during a 44-day observation period in the summer of 2002 using the wet canopy water-budget approach. Holwerda *et al.* (2006) acknowledged that the latter value might be an underestimate, because it was based on observations made during daytime periods during which wind speeds and cloud *LWC* were lower than at night. On the other hand, Holwerda *et al.* (2006) minimized effects of spatial variability in *TF* by the use of 20 roving gages, while in the present study *TF* may have been overestimated because of the use of only two fixed gutters.

Timing of fog-induced throughfall relative to fog interception

Figure 28.2 shows estimated net *CWI* rates together with *TF* and E_w rates during four of the eight events listed in Table 28.2. Half-hourly *CWI* rates as derived from the three types of gages were very similar. All fog events listed generally started by late afternoon or early evening (Figure 28.2). As soon as an event started, E_w became very small, because relative humidity approached 100% and net radiation was close to zero. Figure 28.2 also shows the considerable time lag between the start of a fog event and the start of crown drip. This most probably reflects the filling of the canopy storage *S* (including mosses and epiphytes) since E_w was negligible (cf. Joslin *et al.*, 1990). Under conditions of negligible E_w, the magnitude of the time lag depends on the rate of *CWI* and the effective value of *S*. Whilst the applied event separation period of 3 hours was sufficient to dry up the leaves, a longer period must be required for the drying out of mosses on branches and stems. Hence, the instantaneous (effective) value of *S* will depend on previous wetting and drying cycles (Hölscher *et al.*, 2004; cf. Köhler *et al., this volume*; Mulligan *et al.*, this volume; Tobón *et al.*, this volume #26). The average value of *S* was estimated by integrating calculated *CWI* rates over the duration of the time lag for each *TF*-generating fog event between 5 March and 10 May 2001 ($n = 29$). The mean time lag was about 5 hours (range: 2–12 hours), yielding a mean storage value of about 0.4 mm (range: 0.0–0.7 mm). However, it often took another few hours before *TF* rates became similar to estimated *CWI* rates (Figure 28.2), suggesting that the actual storage capacity was higher than 0.4 mm. A similar process was observed by Chang *et al.* (2002), who measured the increase in weight of (air-dried) bryophytes under foggy conditions in a cypress forest in Taiwan. Fog was seen to begin to drip from the mosses while they were still increasing in weight, i.e. before full saturation was reached (see also discussion in Tobón *et al.*, this volume #26).

CONCLUSIONS

Between 5 March and 10 May 2001, the performance of three passive fog gages (wire harp *WH*, a modified standard fog collector *SC*, and a Juvik-type gage *JU*) was compared at a wind-exposed Puerto Rican elfin cloud forest site.

At low rates of fog incidence, the *JU* indicated shorter fog duration than did either the *WH* or *SC*, probably because of its much smaller collection area (0.052 m^2 vs. 0.25 m^2 for *WH* and *SC*). In general, however, the difference in inferred fog duration according to the three gage types was less than 5%, because dense fog prevailed for 75–80% of the time and winds were sufficiently strong. Gage-to-canopy conversion factors, calculated as the ratio between throughfall (fog drip) and fog collection by the gage during periods of fog-only and negligible evaporation loss, were 0.12 for the *WH* and *SC*, and 0.10 for the *JU*. As a result, estimated mean fog interception rates by the forest using the respective factors were effectively equal at 0.15 ± 0.10 mm hour^{-1} for

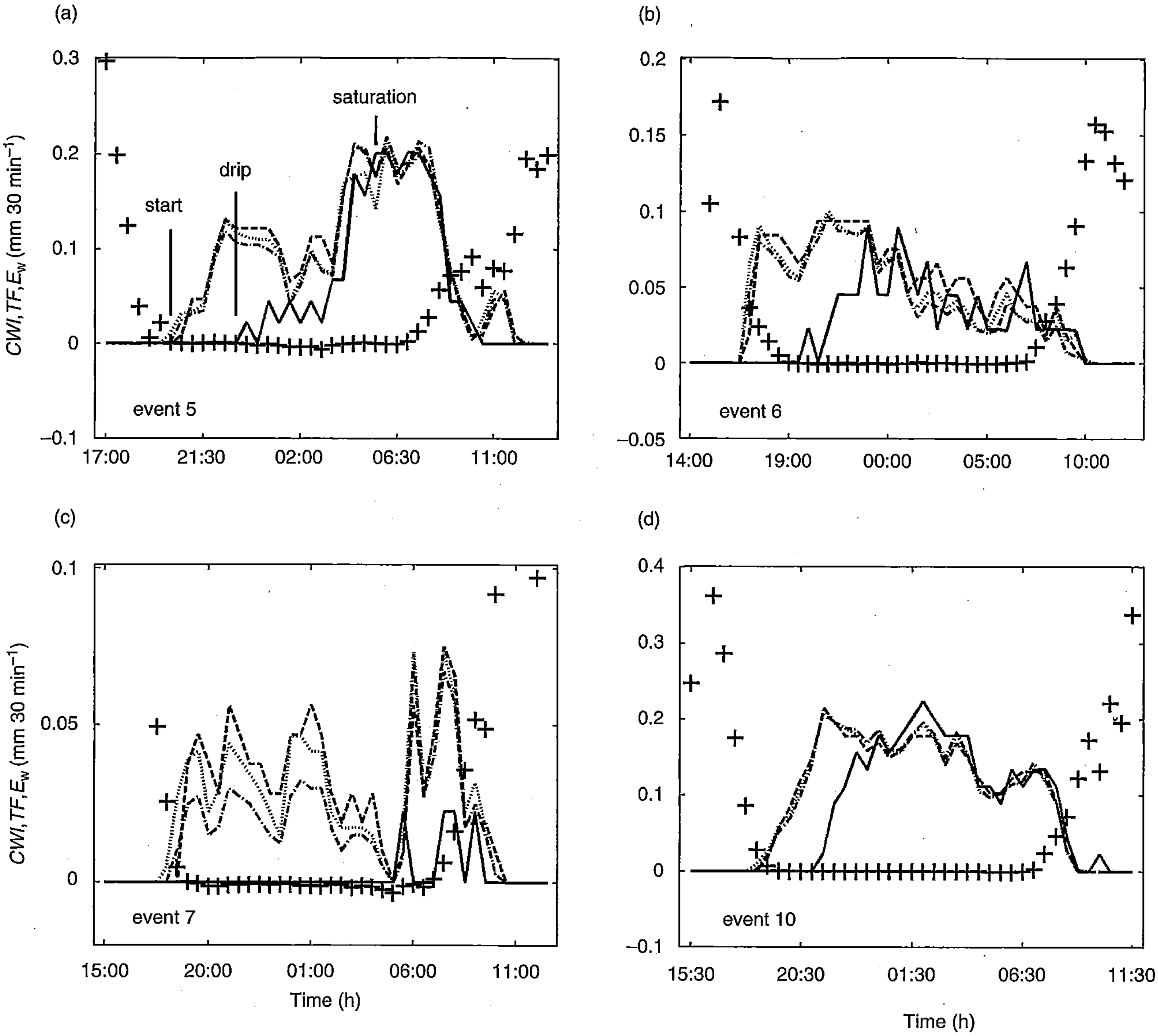

Figure 28.2. Fog deposition rates (*CWI*), as calculated using gauge to canopy conversion factors f_x (Table 28.1), according to the wire harp *WH* (dotted line), standard gage *SC* (dashed dotted line), and Juvik gage *JU* (dashed line) for four selected fog-only events (Table 28.2) between 5 March and 10 May 2001 at Pico del Este. Throughfall *TF* (solid line) and wet canopy evaporation rates E_w (plusses) have been added.

the *WH*, 0.14 ± 0.11 mm hour^{-1} for the *SC*, and 0.15 mm ± 0.11 hour^{-1} for the *JU*.

Throughfall typically started about 5 hours after the fog gages had indicated the start of a fog event. Integrating the estimated fog interception rates over the time lag gave an average value of 0.4 mm for the effective canopy storage capacity.

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 help during the fieldwork and Dr. Robert Schemenauer 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.

Beswick, K. M., K. J. Hargreaves, M. W. Gallagher, T. W. Choularton, and D. Fowler (1991). Size-resolved measurements of cloud droplet deposition velocity to a forest canopy using an eddy-correlation technique. *Quarterly Journal of the Royal Meteorological Society* **117**: 623–645.

Briscoe, C. B. (1966). *Weather in the Luquillo Mountains of Puerto Rico*. Rio Piedras, Puerto Rico: Institute of Tropical Forestry.

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., W. Eugster, and R. Burkard (2005). Fog as an input to the Hydrological cycle. In *Encyclopaedia of Hydrological Sciences*, eds. M. G. Anderson and J. J. McDonnell, pp. 559–582. Chichester, UK: John Wiley.

Chang, S. C., I. L. Lai, and J. T. Wu (2002). Estimation of fog deposition on epiphytic bryophytes in a subtropical montane forest ecosystem in northeastern Taiwan. *Atmospheric Research* **64**: 159–167.

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 Park of Garajonay, La Gomera (Canary Islands, Spain).* PhD Thesis, VU University Ámsterdam, Ámsterdam, The Netherlands. [http://www.falw.vu.nl/nl/onderzoek/earth-sciences/geo-environmental-science-and-hydrology/hydrology-dissertations/index.asp].

Goodman, J. (1985). The collection of fog drip. *Water Resources Research* **21**: 392–394.

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., R. Burkard, W. E. Eugster, *et al.* (2006). 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.

Joslin, J. D., S. F. Mueller, and M. H. Wolfe (1990). Test of models of cloud-water deposition to forest canopies using artificial and living collectors. *Atmospheric Environment* **24A**: 2893–2903.

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.

Juvik, J. O., and D. Nullet (1995a). Comments on "a proposed standard fog collector for use in high elevation regions." *Journal of Applied Meteorology* **34**: 2108–2110.

Juvik, J. O., and D. Nullet (1995b). Relationships between rainfall, cloud-water interception and canopy throughfall in a Hawaiian montane forest. In *Tropical Montane Cloud Forests*, eds. L. S. Hamilton, J. O. Juvik, and F. N. Scatena, pp. 165–182. New York: Springer-Verlag.

Monteith, J. L. (1965). Evaporation and the environment. *Symposia of the Society for Experimental Biology* **19**: 245–269.

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.

Schemenauer, R. S. (1986). Acidic deposition to forests: the 1985 Chemistry of High Elevation Fog (CHEF) Project. *Atmosphere–Ocean* **24**: 303–328.

Schemenauer, R. S., and P. Cereceda (1994). A proposed standard fog collector for use in high-elevation regions. *Journal of Applied Meteorology* **33**: 1313–1322.

Schemenauer, R. S., and P. Cereceda (1995). Reply to comments by Juvik and Nullet (1995). *Journal of Applied Meteorology* **34**: 2111–2112.

Schemenauer, R. S., and P. I. Joe (1989). The collection efficiency of a large fog collector. *Atmospheric Research* **24**: 53–69.

Vong, R. J., J. T. Sigmon, and S. F. Mueller (1991). Cloud water deposition to Appalachian forests. *Environmental Science and Technology* **25**: 1014–1021.

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.