Interception of horizontal precipitation by elfin cloud forest in the Luquillo Mountains, Eastern Puerto Rico

J. Schellekens[+*], L.A. Bruijnzeel[+], A.J. Wickel[+], F.N. Scatena[*] and W.L. Silver[*o]
[+]Vrije Universiteit, Amsterdam, The Netherlands
[*]International Institute for Tropical Forestry, Rio Piedras, Puerto Rico
[o]University of California, Berkeley, USA

Abstract: A preliminary study was made of horizontal precipitation (HP) and throughfall (TF) in two contrasting forest types in the Luquillo Mountains, Puerto Rico, at 265 m (tall Tabonuco forest) and 1050 m (stunted 'elfin' cloud forest, ECF) on the windward side of the island. Measured TF ranged from 48 % of gross rainfall (P) at the lower plot to 89 % at the dwarf forest. The steep gradient in interception loss is thought to be the result of the combined effect of the presence of HP at the upper site, the diminished evaporation potential with elevation and differences in amounts of advected energy. Two shielded Grunow-type fog gauges were used to estimate cloud water input at the ECF. Although a good correlation existed between the two gauges, there was a five-fold difference in catch, illustrating the importance of gauge exposure. The relative contribution of HP during events with rain was too small for separate regressions of TF vs P for events with and without fog to be significantly different. A gauge to canopy multiplication factor of 4.46 was derived for the canopy-level gauge, using HP and TF records for rain-free periods. During a 35-day period the total amount of HP stripped by the ECF was estimated at 46.5 mm or 6.6 % of P and 7.4 % of TF.

1 INTRODUCTION

Tropical montane cloud forests (TMCF) differ from other rain forests in that they are often subjected to horizontal precipitation (HP) inputs and exhibit (very) low transpiration rates [*Bruijnzeel and Proctor*, 1995]. As a result, many TMCFs are of major importance to the water supply of downstream areas [*Zadroga*, 1981]. Although these forests covered about 500,000 km^2 in the 1970s, they are increasingly threatened with conversion to pasture or agricultural cropping [*Hamilton et al.*, 1995]. The effect of TMCF conversion on downstream water yield is unknown but there is presumably a trade-off between the cloud stripping and evaporation characteristics of the original forest and those of the replacing vegetation [*Bruijnzeel and Proctor*, 1995]. Clearly, it is of great practical interest to know which of the two main effects imparted by forest conversion (*i.e.* the loss of HP inputs *vs* reduced rainfall interception) will be dominant and so determine water yield to decrease or increase.

Many TMCFs show some degree of stunting. The reasons for this differ per forest and attempts to find a single unifying factor, be it climatological, soil chemical or physiological, have failed thus far [*Bruijnzeel and Proctor*, 1995]. However, the one environmental factor common to all TMCF is the more or less frequent presence of mist and low cloud, rendering the study of its occurrence and magnitude important for ecological reasons as well.

As part of a collaborative effort of the Vrije Universiteit, Amsterdam (VUA) and the International Institute of Tropical Forestry (IITF), Rio Piedras, the hydrology of the forested Rio Mameyes catchment (17 km^2) in eastern Puerto Rico was studied. *Inter alia*, a reconnaissance study was conducted of fog incidence, rainfall and the interception of both by two contrasting forest types, viz. lowland 'Tabonuco' forest and 'elfin' cloud forest. The present paper offers a preliminary analysis of the precipitation (P, HP) and throughfall (TF) data collected between 30 May and 3 July, 1996.

2 SITE DESCRIPTION

The Luquillo Mountains in eastern Puerto Rico rise to an elevation of about 1050 m a.s.l. over a distance of only 10 km. The Luquillo Experimental Forest (LEF) occupies most of these mountains. The resulting steep climatic gradient, coupled with a continuous supply of moisture-laden air by the trade winds, leads to cloud condensation levels as low as 600-800 m. The vegetation of the LEF consists of four distinct types, the occurrence of which is mainly governed by altitude. Tall broad-leaved Tabonuco forest occurs up to about 600 m, giving way to Colorado and palm forests in the 600-750 m zone. The remaining elevational band around exposed ridges and mountain tops is covered with low (<3 m) 'dwarf' or 'elfin' cloud forest (ECF).

The Tabonuco, Colorado and Palm forest cover 70, 17 and 11 % of the LEF, respectively, leaving about 2 % for the ECF. Whilst the Colorado and palm forests are only occasionally exposed to dense fog and cloud the ECF is frequently enshrouded in mist. Average annual precipitation ranges from 2,500 mm at the base of the mountains to 5,000 mm on the highest peaks, with relatively little seasonal variation [*Brown et al.*, 1983].

3 INSTRUMENTATION AND METHODS

Throughfall at the Tabonuco site (Bisley, 265 m) was measured with 20 non-roving gauges (143 cm^2 each; weekly intervals) and three gutters (0.184 m^2 each) equipped with a tipping bucket *cum* recording system (0.015 mm per tip). The 5-min TF records obtained with the gutters were converted to areal averages by relating gutter totals to the weighted average total of gutters and gauges for each time the gauges were emptied. Rainfall was measured above the canopy at 5-min intervals using a tipping bucket rain gauge (0.254 mm per tip). Ten roving gauges (read at 1-3 day intervals) and three gutters (0.09 m^2 each) were used to measure TF at the ECF site just below a wind-exposed ridge near Pico del Este at 1015 m. Areal averages were computed as in the Tabonocu site. In addition, four 'Grunow' type fog gauges (200 and 628 cm^2 projectional and total wire mesh surface areas; mesh width 1 mm; 100 cm^2 funnel orifice) were used, two of which were shielded against direct rainfall incidence by 1 m^2 roofing. One gauge of each type (*i.e.* covered and non-covered) was equipped with a tipping bucket *cum* recording system (0.44 mm per tip). Amounts of HP were calculated by dividing the volume of water intercepted by the shielded fog gauge by the total collecting surface. Rainfall was measured above the canopy with a similar tipping bucket system (5-min intervals).

4 RESULTS AND DISCUSSION

Table 1 summarizes the magnitude of P, TF and stemflow (SF) at the two study sites for the period 30 May – 3 July, 1996. The striking contrast in the relative amounts of TF observed in the Tabonuco and elfin cloud forests (48 % *vs* 89 %) is thought to reflect the combined effect of the additional input of HP at the upper site, a diminished evaporation potential with elevation, and possibly differences in amounts of advected energy from the nearby ocean. Canopy saturation values of 0.9 and 0.6 mm were derived for the Tabonuco and dwarf forest respectively, using the method of *Gash and Morton* [1978]. Subsequent application of the analytical model of rainfall interception [*Gash*, 1979] suggested average evaporation rates for wet-canopy conditions of 1.25 and 0.35 mm/hr at the Bisley and Pico del Este sites, respectively. These estimates are much higher than the ones obtained with the wet-canopy variant of the Penman-Monteith equation [*Monteith*, 1965], viz. 0.24 and 0.13 mm/hr respectively (*J. Schellekens, unpublished*), implying a roughly five-fold difference in advective energy (1.0 and 0.2 mm/hr) between the sites. Further work is needed to test this contention.

The magnitude of HP at the ECF was studied in two ways: (1) by comparing TF-P relationships during conditions with and without fog (cf. *Harr* [1982]); and (2) by deriving a relationship between amounts of fog caught by the shielded recording Grunow-type gauge and corresponding amounts of TF during all rain-free periods, discarding the first 3 hrs of each period to exclude rainfall-induced TF (and assuming SF is not influenced much by HP). Consequently, rain-free periods shorter than 3 hrs were not used.

As shown in Figure 1a, events with fog generated slightly more TF than fog-free events, although the scatter is such that the relatively small contribution by HP to overall precipitation totals cannot be evaluated reliably in this way (*cf.* the companion paper by *Hafkenscheid et al.*, this volume). Therefore, the potentially more 'direct' alternative method of comparing amounts of HP and TF during rain-free periods was preferred. Dividing corresponding amounts of TF by HP yielded a 'gauge-to-canopy' multiplication factor *c* which theoretically integrates the differences in catch efficiency of the Grunow-type gauge and the tree canopy under consideration. During the period of concurrent operation of the two gauge types 25.3 mm of TF and 5.67 mm of HP were recorded under rain-free conditions, resulting in a *c*-value of 4.46. Applying the latter value to the overall total caught by the shielded canopy-level fog gauge gave an estimated HP total of 46.5 mm during the five-week study period, or 6.6 % of

Table 1: Precipitation components [mm] for the two study sites between 30 May and 3 July, 1996. SF denotes stemflow, other components as indicated previously

	Bisley			Dwarf forest		
Period	P	TF	SF	P	TF	SF
May 30 – Jul 3	388.1	187.0	8.9*	702.2	626.3	35.1+
May 30 – Jul 3 (%P)	100	48.2	2.3*	100	89.2	5+

* Based on data from *Scatena* [1990]. + Based on data from *Weaver* [1972]

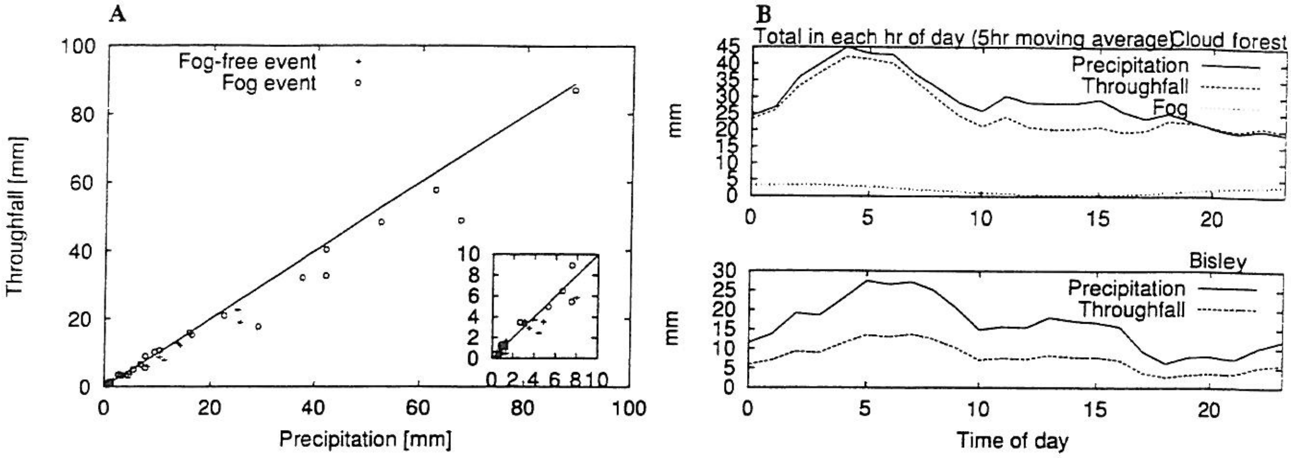

Figure 1: (A) Rainfall *vs* TF at the ECF during events with fog (n=22) and without fog (n=39). Inset shows detail of small storms. (B) Diurnal distribution of cumulative amounts of P, TF and HP at the two study sites between 30 May and 3 July, 1996.

P and 7.4 % of TF. Readings of a manual shielded fog gauge placed at ground level in a nearby grassy clearing showed good correlation with those of the canopy-level gauge ($R^2 = 0.79$, n = 11), but the former caught 5.3 times more fog.

The high sensitivity of (non-shielded) Grunow-type gauges to exposure (wind-driven rain) is one of the major weaknesses of the instrument (*cf. Schemenauer and Cereceda* [1994]) which is why the present analysis is limited to the data collected with the shielded fog gauges. The wind effect is illustrated further by a comparison of Figures 1b and 2. Figure 1b shows the cumulative hourly totals of P, TF and HP (upper site only; based on the multiplication factor of 4.46) for the two forests throughout the study period. Most of the rain falls in the night and early morning at both sites, suggesting the rain to be more orographic than convective in character. The TF:P ratio at Bisley varies relatively little throughout the day, providing further evidence that non-radiant sources of energy are important in determining the high interception fraction. Conversely, at the elfin forest site the TF:P ratio shows a clear depression between 11:00 and 15:00 hr and even exceeds unity between 20:00 and 24:00 hr. The diurnal pattern of fog incidence in Figure 1b mirrors that of the TF:P ratio, suggesting that the occurrence of fog may explain at least part of the variation in relative amounts of TF, although factors like storm size and intensity can play a role as well [*Scatena*, 1990].

The diurnal pattern of fog incidence at the ECF is also strikingly similar to that of wind speed as measured above the canopy (Figure 2). Whilst wind speeds at Bisley reach a maximum around 15:00 hr, the pattern is reversed at 1015 m where the highest wind speeds are recorded at night (*cf. Baynton* [1969]). As such, amounts of fog as indicated by shielded fog gauges seem rather dependent on prevailing wind speed (R^2=0.74, n=24). Grunow-type fog gauges have come under scrutiny for their sensitivity to wind and other factors (*e.g. Schemenauer and Cereceda* [1994]) but their low cost and ease of use have made them the most widely used fog catcher in tropical forest ecological studies until now [*Bruijnzeel and Proctor*, 1995].

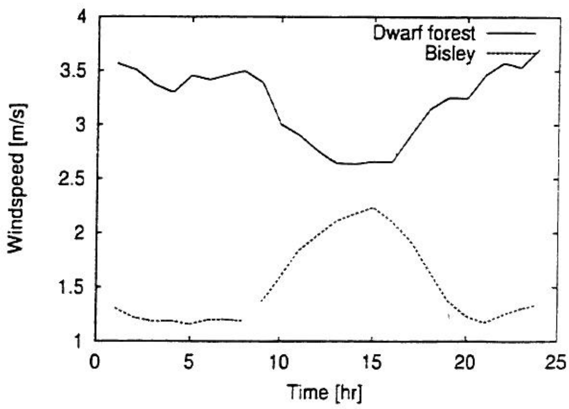

Figure 2: Average diurnal patterns of above-canopy wind speed at the two study sites between 30 May and 3 July, 1996.

Improved estimates of HP in TMCF may be obtained by the use of deposition models [*Lovett*, 1984; *Joslin et al.*, 1990]. However, the information on above-canopy wind speeds, cloud water content and drop-size spectrum required by such models is lacking for tropical montane conditions and a major research effort will be required to fill this gap. The establishment of a pan-tropical network of TMCF sites from which a small number of key sites could be selected for in-depth research could be considered a first step in this direction.

5 SUMMARY AND CONCLUSIONS

Throughfall (TF) on the windward side of the Luquillo Mountains increased from an estimated 48 % in the Tabonuco forest zone at 265 m to ca. 89 % in short-statured elfin cloud forest at 1015 m as a result of extra inputs by horizontal precipitation (HP) at the upper site (see below), decreased evaporation potentials with elevation (roughly 50 % reduction), and differences in advected energy between the two sites (ca. 5 times higher at the base of the mountain). Amounts of TF were not affected sufficiently by inputs of HP to enable a distinction to be made between TF-P relationships for conditions with and without fog. A comparison of corresponding amounts of TF and HP (as recorded by a shielded Grunow-type gauge placed in the top of the canopy) during rain-free periods yielded a gauge-to-canopy multiplication factor of 4.46, resulting in an overall HP figure of 6.6 % of P. The efficiency of the shielded Grunow-type fog catcher was strongly influenced by gauge exposure and wind speed, however. As such, the quoted values for the gauge-to-canopy conversion factor and amount of HP stripped by the forest need to be treated with caution.

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