Estimates of fog interception by montane rain forest in the Blue Mountains of Jamaica

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Abstract: Amounts of cloud water (*CW*) stripped by the canopy of a small-statured ridge top cloud forest at 1825 m in the Blue Mountains of Jamaica were estimated using various approaches, ranging from (i) a comparison of concurrent records of throughfall (*Tf*) and horizontal precipitation (*HP*) during rainless periods; through an analysis of (ii) *Tf vs.* rainfall (*P*) or (iii) *Tf* plus stemflow vs *P* under conditions with and without fog; to (iv) a chloride mass balance approach. Relative amounts of *CW* were all in the range 3.5-5% of *P*. It is concluded that contributions of *HP* are too small to have an adverse effect on water yield following forest conversion to agriculture.

1. INTRODUCTION

Tropical montane cloud forests (TMCF) are among the least studied and understood ecosystems in the tropics. TMCF in headwater areas are generally considered to be of major importance for the water supply of downstream areas because of their allegedly low water use and high fog intercepting ability [*Zadroga*, 1981]. However, recent rainfall interception studies in TMCF in Central America have shown that throughfall in TMCF can be very low (62-65 %), even with significant cloud water inputs [*Cavelier et al.*, 1996, 1997; *Clark et al.*, 1998]. There is some evidence that advected energy from the nearby ocean plays a role in maintaining the required high evaporation rates [*Schellekens et al.*, this volume]. As such, the widespread belief that conversion of TMCF to agricultural cropping or pasture automatically leads to diminished water yield, would seem unfounded. The discussion about the hydrological impacts of TMCF conversion is hampered, however, by a lack of reliable data on forest water use and on the amounts of cloud water actually stripped by the vegetation [*Bruijnzeel and Proctor*, 1995].

Many TMCF are reduced in stature and an array of (sometimes mutually contradictory) hypotheses have been advanced to explain the phenomenon [*Bruijnzeel and Veneklaas*, 1998; *Hafkenscheid*, 1998]. However, the one environmental factor common to all TMCF is the more or less frequent presence of mist or low cloud, making the study of its occurrence and magnitude important for ecological reasons as well.

As part of a program investigating the causes of forest stunting on tropical mountains, the hydrology and biogeochemistry of two adjacent TMCF of contrasting stature in the Blue Mountains of Jamaica were studied in detail between January 1995 and April 1996. This paper discusses the magnitude of the main precipitation components in the smaller of the two forests, paying particular attention to the quantification of horizontal precipitation.

2. SITE DESCRIPTION

Montane forests above 1300 m in the Blue Mountains show striking contrasts in stature, soil development and ecological functioning, even under apparently similar geological and climatic conditions [*Tanner*, 1977; 1980]. The stunted (maximum tree height c. 8.5 m) ridge top forest selected for detailed hydrometeorological and biogeochemical studies is situated at 1825 m (18° 05' 29" N; 76° 38' 57") on a SW-orientated spur between Sir John's Peak (1900 m) and Bellevue Peak (1849 m), the distance between the latter and the plot being <150 m. The site is well-exposed to the prevailing winds (*cf.* Figure 1). Average annual rainfall is c. 2850 mm, with large differences between years. October and November are very wet (>350 mm each) whereas March and July are relatively dry (<90 mm). Fog and low cloud occur mostly on northerly slopes, usually between 10:00 and 16:00 hr but rarely at night. Showers are generally of short duration and tend to fall in the mid-afternoon, with minimum rainfall in the evening (Figure 2), suggesting the rain to be convective rather than orographic. A detailed description of the physiognomy, floristics and soil of the forest plot has been given by *Hafkenscheid et al.* [1998].

3. INSTRUMENTATION AND METHODS

A meteorological mast, extending 9 m above the surrounding scrub (3.5 m) on Bellevue Peak provided continuous records of the chief climatological

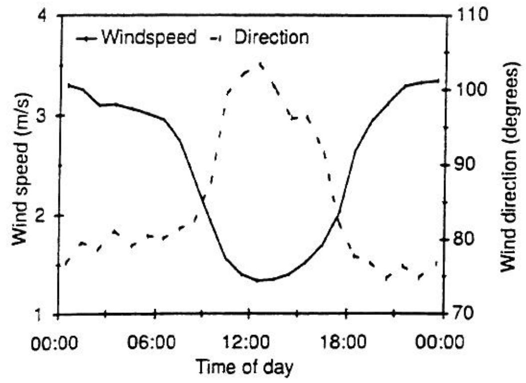

Figure 1: Average diurnal patterns of above-canopy wind speed (at 11.2 m) and direction at Bellevue Peak (1849 m) between 1 January 1995 and 13 April 1996.

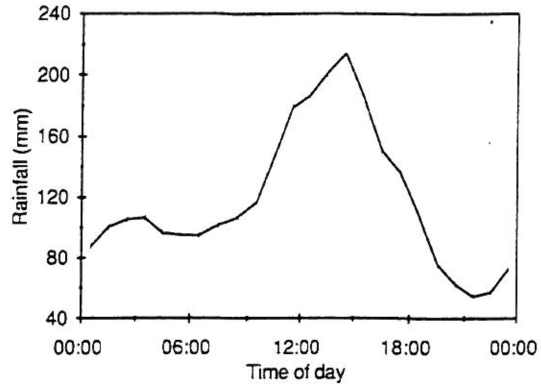

Figure 2: Diurnal distribution (5-hr moving averages) of cumulative amounts of rainfall at Bellevue Peak between 1 January and 13 April 1996.

parameters. Rainfall (*P*) was measured above the canopy with a 0.44 mm capacity tipping bucket *cum* logger system backed up by two manual gauges placed in a nearby clearing. Horizontal precipitation (*HP*, fog plus wind-driven rain) was recorded above the canopy using an identical logger system connected to a non-shielded 'Grunow'-type fog gauge (200 and 628 cm^2 projectional and total wire mesh surface areas; mesh width 1 mm). Records of *P* and *HP* were stored at 5-min intervals. In addition, one non-shielded and one shielded (75 x 75 cm tarpaulin cover) manual fog gauge (read at 3-4 day intervals) were installed in the clearing at 1.5 m above ground level. The volumes collected by the sheltered fog gauge were taken to provide a first estimate of fog incidence (*F*) and were converted to mm of water by dividing by the total area of the wire mesh cylinder. Amounts of *HP* were also measured above the forest plot using automated equipment identical to that used on Bellevue Peak. Throughfall (*Tf*) in the forest was measured with a tilted stainless steel gutter (0.14m^2) equipped with a tipping bucket device (0.3 mm per tip) in combination with twelve roving manual gauges (3-4 day sampling intervals). Stemflow (*Sf*) was measured on twelve trees representing a range of diameter classes using rubber collars connected to 5-gallon containers which were emptied at the same times as the *Tf* and shielded fog gauges. Dividing *Sf* volumes by the projectional area of the tree crowns enabled their expression in mm of water.

4. RESULTS AND DISCUSSION

Table 1 summarizes the total amounts of *P*, *Tf* and *Sf* during the 469-day study period (1 January 1995 - 13 April 1996), from which the corresponding amount of intercepted rainfall (*Ei*) was derived by difference. Of

Table 1: Precipitation at Bellevue Peak and its components (manual gauge data) in the ridge top forest between 1 January 1995 and 13 April 1996.

	Bellevue Peak	Stunted forest		
	P	*Tf*	*Sf*	*Ei*
mm	4880	3019	1028	833
(%)	100	62	21	17

the 469 days covered by the study, 267 days had rain (*P*>0.44 mm), giving an average of 18.3 mm per rain day. However, the observation period included an exceptionally large composite storm which delivered >1200 mm over a 4-5 day period in February 1996. Excluding this extreme event gives an average rainfall amount of 14.0 mm per rain day. However, the frequency distributions of storm size, intensity and duration were all highly skewed, justifying the use of median rather than mean values. Median values for storm size, duration and intensity were 1.76 mm, 1:02 h and 1.57 mm h^{-1}, respectively. About 40% of all events were <1 mm and c. 80% were <10 mm.

The *Sf:P* ratio for the study forest is very high compared to values reported for other TMCF, rendering the *Tf:P* ratio very low [*Bruijnzeel and Proctor*, 1995; *cf. Cavelier et al.*, 1997]. This is presumably caused by the high proportion of leaning and multi-stemmed trees [*Hafkenscheid et al.*, 1998].

The poor performance of non-shielded Grunow-type fog gauges in windy conditions is illustrated by the fact that the above-canopy gauges at Bellevue Peak and the forest plot recorded a surplus of 12 and 22% over *P*, suggesting considerable 'contamination' by wind-driven rain, whereas the non-shielded gauge in the clearing on Bellevue Peak collected only 0.1% of *HP*. The adjacent shielded gauge recorded 190 mm of fog (3.9% of *P*), providing further evidence that subtracting two large amounts (*P* and *P+HP*) to obtain a smaller amount (*F*) by difference is a hazardous affair for non-shielded gauges exposed to wind [*cf. Schemenauer and Cereceda*, 1994].

Four approaches were followed to estimate amounts of fog and low cloud stripped by the ridge top forest (termed *CW* hereafter to distinguish this input from *HP* and *F* as measured by the non-shielded and shielded Grunow-type gauges), viz.: (i) the comparison of amounts of *Tf* and *HP* (recording gauges) during rainless periods, discarding the first 2 hrs after rainfall stopped to avoid the inclusion of rain-induced *Tf*; (ii) the comparison of *Tf-P* relationships (recording gauges, daily values; *P*<100 mm) for *events* with and without fog [*cf. Harr*, 1982], assuming events to be fog-free whenever *F* <0.01 x *P* (both in mm of water); (iii) *idem* for *Tf*- and *(Tf+Sf)-P* relationships (*3-4 day periods*); and (iv) the chloride budget approach [*Uhlrich*, 1983].

Ad (i) *Tf vs HP* during rainless conditions: The implicit assumption of this approach is that for the selected sample periods all of the recorded *HP* can be considered to represent cloud water. The 93 mm of *Tf* which were generated during the rain-free periods for which concurrent recordings of *Tf* and *HP* were available represented 3.4% of the total rainfall associated with the respective preceding storms. It is recognized that the application of the 2-hr threshold (which is based on the relative magnitudes of the canopy evaporation value and the average wet-canopy evaporation rate; *R.L.L.J. Hafkenscheid, unpublished*) will inevitably lead to an underestimation of absolute and relative values of *CW*. Dividing the cloud-water generated *Tf* total by the corresponding amount of *HP* measured above the canopy gave a gauge to canopy multiplication factor *c* of 1.12. *Schellekens et al.* [this volume] obtained a value of 6.6% of incident *P* for a low-stature (<3 m) 'elfin' cloud forest at 1015 m in Puerto Rico using nearly identical methodology.

Ad (ii) *Tf-P* relationships for rainfall *events* with and without fog: Although the respective regression equations had reasonable coefficients of determination (R^2 = 0.891 for 30 fog-free events *vs.* 0.805 for 155 events with fog), their slopes were almost identical at 0.639 (fog-free events) and 0.658 (fog events). As a result, the average *Tf:P* ratios for the two conditions were also very similar (0.69 and 0.67, respectively), rendering a comparison of the two situations for the evaluation of fog-induced *Tf* meaningless from the statistical point of view. Nevertheless, taking the two regressions at face value, the extra *Tf* generated by the presence of fog or low cloud would be 85 mm or 5.0% of the associated amount of *P*. Repeating the exercise for the manually measured *Tf* data (3-4 day periods) gave a slightly smaller value (79 mm or 4.2%).

Ad (iii) *(Tf+Sf)-P* relationships for *3-4 day periods* with and without fog: To assess the influence of the exclusion of *Sf* (which was measured manually only) in method (ii), the computations were repeated with the *Tf+Sf* data set. However, the scatter about the two regression lines (Figure 3) was such that the slope value of 0.78 for the relationship for fog-free periods (*n*=32, R^2=0.90) did not differ significantly (at 95% probability level) from the figures obtained for periods with fog (0.83, *n*=76, R^2=0.88).

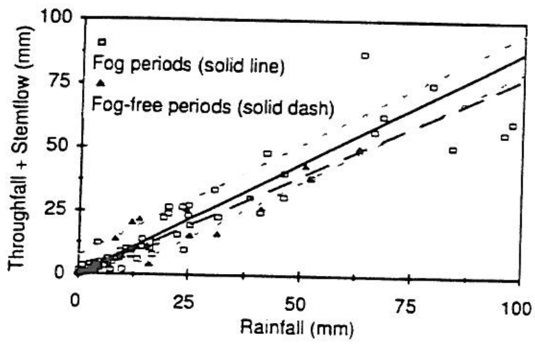

Figure 3: Rainfall *vs.* throughfall plus stemflow during *periods* with fog (*n*=76) and without fog (*n*=32). The light dashed lines represent 95% confidence limits.

Nevertheless, the 'direct' application of the two regressions resulted in an estimated amount of fog-induced *Tf+Sf* of 94 mm (5.0% of *P*). Comparing the latter value with the corresponding total collected with the shielded fog gauge at Bellevue Peak (117 mm) yielded a gauge to canopy multiplication factor *c* of 0.80. In this case the *c*-factor not only includes any differences in the collecting efficiencies of the gauge and the forest (as in method (i) where *HP* was measured on the site) but also reflects potential differences in fog characteristics between Bellevue Peak and the ridge top plot.

Ad (iv) Chloride budget: If the amounts of certain chemical elements that are not taken up in significant quantities by the vegetation (such as chloride) in *P*, *Tf* and *Sf* are known, then the amount of cloud water stripped by the forest canopy can be computed from the concentration of that element in cloud water using a mass balance approach [*Uhlrich*, 1983]:

$$(P \cdot C_P) + (CW \cdot C_{CW}) = (Tf \cdot C_{Tf}) + (Sf \cdot C_{Sf}) \qquad (1)$$

in which *P*, *CW*, *Tf* and *Sf* are as defined before (mm) whereas the various subscripts of *C* denote the respective concentrations of chloride. Application of equation (1) gave an estimated value for *CW* of 128 mm (3.5% of *P*), which is close to the estimate obtained with method (i) and somewhat smaller than the other estimates (4.2-5%).

5. SUMMARY AND CONCLUSIONS

Various approaches to estimate amounts of cloud water (*CW*) intercepted by a low-stature ridge top cloud forest in the Blue Mountains of Jamaica suggested values of 3.4-5.0% of incident rainfall (*P*). Although the evaluation of *CW* by comparing relationships between *P* and net rainfall (be it throughfall (*Tf*) alone or *Tf* plus stemflow) for conditions with and without fog suffered from a large scatter in the data, the results (4.2-5.0%) were similar to values obtained with a shielded Grunow-type fog gauge (3.9%) and the chloride mass balance technique (3.5%). It is concluded that, despite the uncertainty of the present estimates of *CW*, such contributions are small, suggesting that serious adverse effects on total water yield due to the loss of *CW* inputs following forest conversion to agriculture are not to be expected. In theory, improved estimates of *CW* in TMCF may be obtained through the use of physically based fog deposition models [*e.g. Joslin et al.*, 1990]. However, the necessary data on liquid water content and drop-size spectrum of fog or low cloud are lacking for remote tropical mountain sites such as the Blue Mountains. As such, investigations of fog/cloud characteristics at a few selected TMCF sites would be a major step towards improved quantification of the contributions by horizontal precipitation to the water balance of TMCF.

6. ACKNOWLEDGEMENT

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REFERENCES

Bruijnzeel, L.A., and J. Proctor, 1995: Hydrology and biochemistry of tropical montane cloud forests: what do we really know?, pp. 38-78 in *Ecological Studies no. 110*, Springer-Verlag, New York.

Bruijnzeel, L. A., and E. J. Veneklaas, 1998: Climatic conditions and tropical montane forest productivity: the fog has not lifted yet, *Ecology*, *79*, 3-9.

Cavelier, J., D. Solis, and M. A. Jaramillo, 1996: Fog interception in the montane forests across the Central Cordillera of Panamá, *J. Trop. Ecol.*, *12*, 357-369.

Cavelier, J., M. Jaramillo, D. Solis, and D. de León,1997: Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama, *J. Hydrol.*, *193*, 83-96.

Clark, K. L., N. M. Nadkarni, D. Schaeffer, and H. L. Gholz, 1988: Atmospheric deposition and net retention of ions by the canopy in a tropical montane forest, Monteverde, Costa Rica, *J. Trop. Ecol.*, *14*, 27-45.

Hafkenscheid, R. L. L. J., 1998: Montane rain forest in the Blue Mountains, Jamaica: forest stature and edaphic conditions, *Acta Botanica Neerlandica*, 47, in press.

Hafkenscheid, R. L. L. J., L. A. Bruijnzeel, R. Hogervorst, L. Spijkerman, and H. A. Verhoef, 1998: Two montane rain forests of contrasting stature in the Blue Mountains, Jamaica: a quantitative characterization of their floristics, biotics and soils, *J. Trop. Ecol.*, under review.

Harr, R. D., 1982: Fog drip in the Bull Run municipal watershed, Oregon, *Wat. Resour. Bull.*, *18*, 785-789.

Joslin, J. D., S. F. Mueller, and M. H. Wolfe, 1990: Tests of models of cloudwater deposition to forest canopies using artificial and living collectors, *Atm. Env.*, *24A*, 3007-3019.

Schemenauer, R. S., and P. Cereceda, 1994: A proposed standard fog collector for use in high-elevation regions, *J. Appl. Meteo.*, *33*, 1313-1322.

Tanner, E.V.J., 1977: Four montane rain forests of Jamaica: a quantitative characterization of the floristics, the soils and foliar mineral levels, and a discussion of the interrelations, *J. Ecol.*, *65*, 883-918.

Tanner, E.V.J., 1980: Litterfall in montane rain forests of Jamaica and its relation to climate, *J. Ecol.*, *69*, 833-848.

Uhlrich, B., 1983: Interaction of forest canopies with with atmospheric constituents: SO_2, alkali and earth alkali and chloride, pp. 35-45 in B. Uhlrich and J. Pankrath (eds.), *Effects of Accumulation of Air Pollutants in Forest Ecosystems*, D. Reidel, Dordrecht, The Netherlands.

Zadroga, F., 1981: The hydrological importance of a montane cloud forest area of Costa Rica, pp. 59-73 in E.W. Russell and R. Lal (eds.), *Tropical Agricultural Hydrology*, John Wiley & Sons, New York.