# Stable isotopes in rainfall and fog in the Luquillo Mountains, eastern Puerto Rico: a preliminary study

A.H. te Linde+, L.A. Bruijnzeel+, J. Groen+, F.N. Scatena# and H.A.J. Meijer*
+Faculty of Earth Sciences, Vrije Universiteit, Amsterdam, The Netherlands
#International Institute of Tropical Forestry, Rio Piedras, Puerto Rico, U.S.A.
*Centre for Isotope Research, University of Groningen, Groningen, The Netherlands

Abstract: Weighted mean mass-balance based estimates of fog interception (*CW*) by montane forest at Pico del Este, Puerto Rico varied from 15.6 ± 6.9% of rainfall using electric conductivity values of rain, throughfall, stem flow and fog, to 11.9% using the stable isotope $^{18}$O (range: 4.2-23.2%). The latter estimate agreed rather well with amounts collected by a large screen protected against wind-driven rain (61.6 vs. 57.4 mm) over a 35-day period. Conversely, the EC-based value was considered an overestimate due to a dry deposition of sea salts effect. Rainfall showed very little depletion of stable isotopes with altitude, suggesting re-evaporation of intercepted rain to be important. Fog was isotopically very similar to rainfall, suggesting the fog to be of local origin.

## 1. INTRODUCTION

To explain the very high amounts of rainfall intercepted by tall lowland and colline forests in the Caribbean (up to 50% of rainfall *P* and far in excess of available amounts of radiant energy), Schellekens *et al*. [2000] hypothesized that the energy required to sustain such high levels of wet canopy evaporation might be supplied by advection of sensible heat from the surrounding seas and/or by latent heat released upon condensation of water vapor produced by evaporation of intercepted rain (*Ei*). Some support for this ‘condensation hypothesis’ was derived from the fact that *Ei/P* proved independent of storm size, suggesting a positive feedback of rainfall amount on *Ei* [Schellekens *et al.*, 2000]. Also, there is indirect evidence that the very high evapotranspiration maintained by these forests affects the level of cloud condensation, thereby influencing in turn amounts of fog captured by headwater cloud forests. Scatena and Larsen [1991] reported a temporary rise in the level of the cloud base after the forest on the windward side of the Luquillo Mountains in Puerto Rico had been defoliated by Hurricane Hugo. The associated drop in forest *ET* caused a rise in air temperatures and thus in the level of cloud condensation. The effect disappeared after the leaves had grown back (cf. photographs in Bruijnzeel and Hamilton [2000], p.24).

The quantification of fog interception by forest vegetation (*CW*) is difficult. The classic approach of comparing amounts of net precipitation (throughfall *Tf* plus stemflow *Sf*) measured inside the forest with gross rainfall *P* for events with and without fog [Harr, 1982] only works well where fog contributions are substantial and confidence limits for *Tf* + *Sf* narrow. Sodium- or chloride mass balance techniques tend to overestimate *CW* where dry deposition of sea salt occurs [Hafkenscheid, 2000]. Dawson [1998] successfully used the contrast in stable isotope signatures between rainfall and advective sea fog to evaluate the contribution of *CW* to a coastal redwood forest. A similar contrast has been reported for rain and fog under dry continental tropical conditions [Ingraham, 1998].

This preliminary study explores the usefulness of stable isotopes (notably $^{18}$O and $^{2}$H) for assessing the magnitude of *CW* in a stunted ‘elfin cloud forest’ under wet and windy conditions at Pico del Este, Luquillo Mountains, eastern Puerto Rico. The paper also examines the changes in isotope content of rain water with elevation in an attempt to shed some more light on the ‘condensation hypothesis’.

## 2. STUDY AREA

The largely forested Luquillo Mountains rise to an elevation of about 1050 m a.s.l. over a distance of only 10 km. The resulting steep climatic gradient, coupled with a steady supply of moisture-laden air from the Atlantic Ocean by the north-easterly trade winds, leads to a general cloud condensation level between 600 and 800 m a.s.l. Tall broad-leaved lower montane forest is found up to about 600 m, giving way to upper montane forest between 600-900 m, followed by stunted (2-3 m) ‘elfin’ cloud forest (ECF) on exposed slopes and ridges above 900 m. The UMF forest experiences regular fog of variable density but the ECF is frequently enveloped in dense fog. Branches and stems in both UMF and ECF are largely covered with mosses and epiphytes [Weaver, 1995]. The climate is maritime tropical and characterized by frequent (up to 1600 per year) showers of mostly low intensity (± 3 mm/hr). Rain originates largely from orographic cooling and shows relatively little seasonal variation, although high-intensity convective rainfall occurs as well. Annual rainfall increases with elevation (from 2600 mm to 5000 mm; García-Martíno *et al.,* 1996]. On average, a major hurricane passes over the Luquillo Mountains about once every 60 years [Scatena and Larsen, 1991].

## 3. METHODS

Eight sites, spread more or less evenly along the altitudinal gradient (cf. Fig. 1) were selected to measure and sample rainfall on a daily basis. The gauges used had 250 $cm^2$ plastic funnels mounted onto 1-gallon plastic containers and were placed above the canopy or in large clearings. At 350 m (Bisley tower) and at 1015 m (ECF) rainfall was recorded at 5-minute intervals using a tipping bucket gauge (0.254 mm per tip). Throughfall at Bisley and in the ECF was measured using three steel gutters (300 x 6.3 cm) draining into 5-gallon containers and placed at an angle of $20^o$ to minimize splash effects. *Tf* at Bisley was measured using 10 roving manual gauges as well. Stemflow was not measured because good estimates were available for both forests [2.3% and 5% of *P*, respectively; Scatena, 1990; Weaver, 1972] but stemflow in the ECF was collected for analysis using a 1 m rubber hose cut in half around the stem of a 'typical' tree. A 1 m x 1 m wire mesh fog screen (mesh width 1 mm) was erected on a freely exposed ridge at the ECF site with its base at 1 m. The screen was protected from wind-driven rain by a 2 m x 3 m plastic sheet placed above it. A 100 x 6 cm gutter at the bottom of the screen led the drip into a 1-gallon container from which a daily sample was taken.

Thirty-four precipitation events were sampled between 4 September and 9 October 1999, of which 7 were selected to represent different storm size classes. The samples of rain, throughfall, stemflow and fog water were stored in poly-sealed 10 cc glass bottles and sent to Amsterdam to be forwarded to the Centre for Isotope Research at Groningen, The Netherlands, for stable isotope analysis. Because a first batch of samples was lost in the mail between Amsterdam and Groningen only five events could be analyzed in the end. Stable isotope composition was determined from a gas sample generated from pure liquid and introduced into a SIRA-9 isotope ratio mass spectrometer. $^2H$ concentrations were measured using the uranium reduction method and $^{18}O$ concentrations using the $CO_2$-water equilibration method [Epstein and Mayeda, 1953]. Values are denoted in the customary delta notation (in $^0/_{00}$) in which the ratios of heavy to light isotopes (i.e. $^2H/H$ and $^{18}O/^{16}O$) are expressed relative to those in the general standard (V-SMOW or Vienna Standard Mean Ocean Water). In the following these will be referred to as $\delta^2H$ and $\delta^{18}O$ for the stable hydrogen and oxygen isotope ratios, respectively [Kendall and Caldwell, 1998].

## 4. RESULTS AND DISCUSSION

Rainfall totals between 4September and 9 October 1999 ranged from 177 mm at Luquillo Beach (2 m a.s.l.) to 517 mm at the Elfin Forest site (1016 m), with intermediate stations receiving 329-479 mm. Average storm size was close to 15 mm (100-915 m elevation range) but distinctly lower at the coast (8.4 mm) and higher near the summit (24.6 mm). There was a strong correlation between site elevation and event rainfall ($R^2$=0.82), suggesting strong orographic control of rainfall. The average electric conductivity (EC, taken as a measure of dissolved sea salts) of the rain was highest at the beach location (27.5 μSiemens/cm) but surprisingly constant (15.5 ± 1.5 μSiemens/cm) above 200 m elevation, despite increases in distance to the ocean and dilution by rainfall.

To further explore the possibility of rainfall enrichment (be it in sea salts or stable isotopes) with elevation by repeated evaporation and condensation cycles [Schellekens *et al.*, 2000], the $\delta^{18}O$ contents of the rain associated with five individual storms (Figs. 1, 2) were compared with theoretically derived values using so-called Rayleigh distillation equations. The latter describe the partitioning of isotopes between two 'reservoirs' (e.g. the liquid and vapor fractions within an air mass) as one reservoir decreases in size (e.g. during evaporation or rain-out) (see Kendall and Caldwell [1998] for details and boundary conditions). As rain condenses, the heavier isotopes ($^2H$, $^{18}O$) are preferentially removed from the air mass (rained out). This is why rainfall becomes progressively lighter isotopically ('depleted') as a storm moves inland from the ocean. The effect is enhanced further by the associated drop in temperature with elevation. However, when part of the rained-out moisture is returned to the atmosphere (e.g. via evaporation of intercepted rainfall), then depletion will be (much) less than predicted by the Rayleigh model [Ingraham, 1998]. Fig. 2 illustrates this phenomenon for a storm occurring on 19 September that delivered 13 mm at Bisley and 7 mm at ECF (in 4-5.5 h). Patterns observed for three other storms of similar magnitude (10-20 mm) and wind direction (N-NW) were very similar (not shown here). Above ca. 300 m, the rain becomes gradually less depleted in $^{18}$O than predicted by Rayleigh theory (assuming 100% rain-out by the time the air mass has reached the summit). The discrepancy remained after allowing 50% of the rain to 'spill over' (see right hand side of Fig. 2). Based on relative rainfall totals on either side of the mountain, 50% spill over is considered a reasonable value for the average-sized storms under consideration. Interestingly, the two lines only start to diverge beyond the first two sampling stations which mark the beginning of closed forest. Below Sabana the area is not densely vegetated. Rainfall interception and thus isotope enrichment via re-evaporation can therefore be expected to be low. The observed $\delta^{18}$O depletion rate of less than $-2.6\ ^0/_{00}$ per 1000 m rise in elevation or 10 km of inland travel (Fig. 2) is less than generally reported [Ingraham, 1998; Tang et al., 1998], thereby confirming the importance of local re-evaporation of (intercepted) rainfall.

Fig. 3 displays the $\delta^{18}$O vs. $\delta^2$H contents of *P*, *Tf* and *CW* (where present) for the five sample storms at 350 m, 910 m and 1015 m (sites denoted Bisley, Palm and Elfin, respectively). Whilst rainfall interception *Ei* at 350 m (tall lower montane forest) was high at 34% of *P* compared to 12% in upper montane palm and –7.5% (indicating net addition of water by fog stripping) in elfin cloud forest, the relative enrichment of $\delta^{18}$O in *Tf* at Bisley was not commensurate. Such discrepancies are perhaps due to 'selective canopy storage' (see DeWalle and Swistock [1994] for discussion). Despite the small size of the present data set, a comparison of weighted mean values of $\delta^{18}$O in *P* and *Tf* at the respective sites showed *Tf* to be enriched at Bisley and in the palm but (slightly) depleted within the cloud affected zone (Fig. 3). Further work is needed.

The fog samples plot in the middle of the rain water samples, regardless of storm size (Fig. 3). In contrast to observations elsewhere [Ingraham, 1998; Dawson, 1998], the fog at Pico del Este is not enriched in $\delta^{18}$O or $\delta^2$H, confirming the view that the fog is of local origin. The same can be said of the smaller storms depicted in Fig. 3 (top right hand corner) whereas the much more depleted values associated with the large storm of 28 September (bottom left hand corner) suggests repeated rain-out from an air mass of more remote origin (which is in line with the southerly wind direction observed during this particular event). The general mass balance equation in which *C* denotes the concentration of a constituent:

$$(P \times C_P) + (CW \times C_{CW}) = (Tf \times C_{Tf}) + (Sf \times C_{Sf}) \quad (1)$$

was solved to estimate fog deposition *CW* at the elfin forest site.

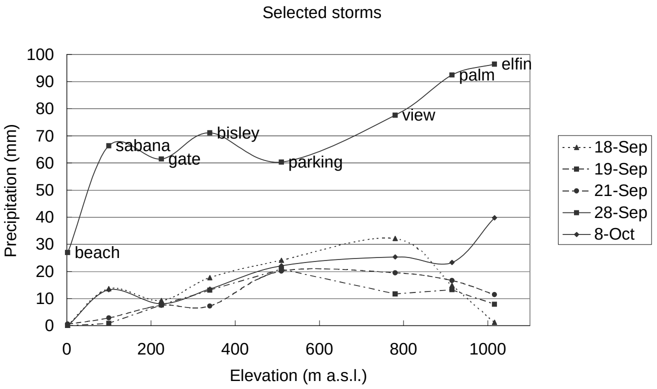

Fig. 1. Amounts of rainfall associated with the five sampled storms at different elevations.

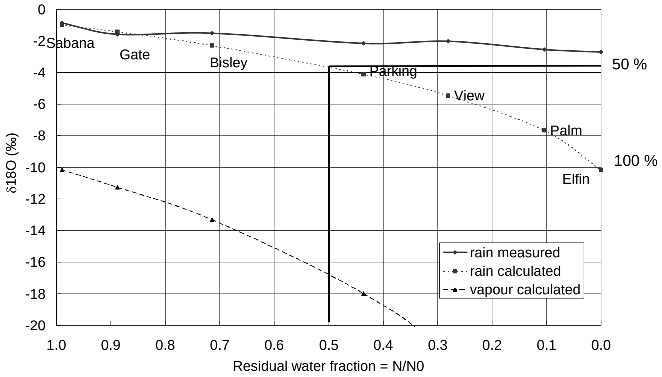

Fig. 2. Predicted vs. observed $\delta^{18}$O values in rainfall with elevation (see text for explanation).

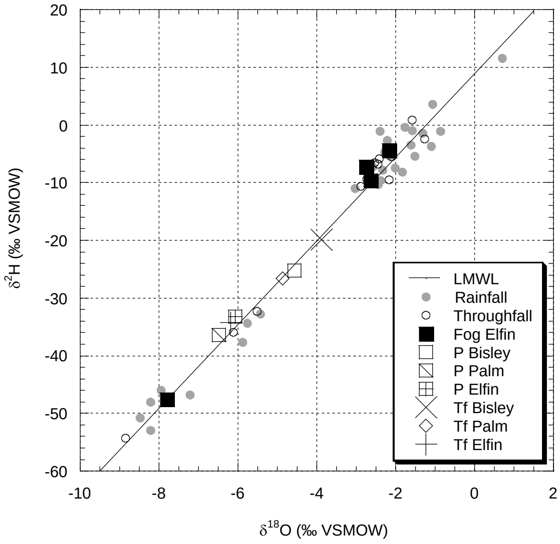

Fig.3. $\delta^{18}$O vs. $\delta^2$H contents of rain, throughfall and fog water (where present) at three elevations.

Measured amounts of *P* and *Tf* and estimated [Weaver, 1972] amounts of *Sf* were used in combination with the respective $\delta^{18}O$ ($n$ = 4) and EC ($n$ = 34) 'concentrations' in *P*, *CW*, *Tf* and *Sf*. The resulting EC-based weighted mean value for *CW* was 15.6 ± 6.9% of *P*, which almost certainly represents an overestimate in view of the likely effect of dry deposition of sea salts on the canopy in this maritime environment [Asbury *et al.*, 1994]. Comparative $\delta^{18}O$-based estimates for individual storms varied between 4.2% for a 40 mm storm and ca. 22% for two storms of 8-12 mm, with an overall weighted mean of 11.9% of *P*. This is intermediate between the ca. 7% obtained by Baynton [1969] and Schellekens *et al.* [1998] at the same location (who used a lowered fog gauge and measurements of net precipitation during rainless periods, respectively) and the previous EC-based estimate. Incorporating the isotope-based estimate of *CW* into the overall apparent *Ei* value of -7.5% derived from the measurements of gross and net rainfall cited earlier yields a net value of 4.4%. In view of the prevailing climatic conditions (persistent high humidity, low radiation) the latter result is encouraging although more elaborate sampling for isotope analysis is obviously required. Finally, the large fog screen (protected against wind-driven rain) collected 57.4 mm of fog between 4 September and 9 October 1999. This agrees well with the isotope-based (extrapolated) total of 61.6 mm. Arguably, such a finding may be interpreted as further support for the credibility of the isotope-based estimate of *CW*.

## 5. ACKNOWLEDGEMENT

We thank Guido van der Werf and Carlos Estrada for assistance in the field and Bert Kers and Janette Spriensma (CIR-RUG, stable isotopes) for their help in the laboratory.

## REFERENCES

Asbury, C.E., W.H. McDowell, R. Trinidad and S. Berrios, 1994: Solute deposition from cloud water to the canopy of a Puerto Rican montane forest. *Atm. Env.*, Vol. 28, 1773-1780.

Baynton, H.W., 1969: The ecology of an elfin forest in Puerto Rico. 3. Hilltop and forest influences on the microclimate of Pico del Oeste. *J. Arnold Arbor*., Vol. 50, 80-92.

Bruijnzeel, L.A. and L.S. Hamilton, 2000: Decision Time for Cloud Forests. *IHP-Humid Tropics Progr. Ser*. No. 13. UNESCO, Paris, 40 pp.

Dawson, T.E., 1998: Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecol.*, Vol. 117, 476-485.

DeWalle, S.R. and B.R. Swistock, 1994: Differences in $^{18}O$ content of throughfall and rainfall in hardwood and coniferous forests. *Hydrol. Proc*., Vol. 8, 75-82.

Epstein, S. and T.K. Mayeda, 1953: Variations of $^{18}O$ content of waters from natural sources. *Geochim. Cosmochim. Acta*, Vol. 4, 213-224.

García-Martíno, A.R., F.N. Scatena, G.S. Warner and D.L.Civo, 1996: Rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico. *Caribb. J. Sci.,* Vol. 32, 413-424.

Hafkenscheid, R.L.L.J., 2000: Hydrology and biogeochemistry of montane rain forests of contrasting stature in the Blue Mnts. of Jamaica. PhD Thesis, Vrije Universiteit, Amsterdam.

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

Ingraham, N.L., 1998: Isotopic variations in precipitation. In: C. Kendall and J. McDonnell (eds.), *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam, pp. 98-118.

Kendall, C. and E.A. Caldwell, 198: Fundamentals of isotope geochemistry. In: C. Kendall and J. McDonnell (eds.), *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam, pp. 51-86.

Scatena, F.N., 1990: Watershed scale rainfall interception on two forested watersheds in the Luquillo Mountains of Puerto Rico. *J. Hydrol.*, Vol. 113, 89-102.

Scatena, F.N. and M.C. Larsen, 1991: Physical aspects of hurricane Hugo in Puerto Rico. *Biotropica*, Vol. 23, 317-323.

Schellekens, J. et al. 1998: Interception of horizontal precipitation by elfin cloud forest in the Luquillo Mountains, eastern Puerto Rico. In: R.S. Sche-menauer and H.A. Bridgman (eds.). *First Inter-national Conference on Fog and Fog Collect-ion*. IDRC, Ottawa, Canada, pp. 29-32.

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 Resour. Res.*, Vol. 36, 2183-2196.

Tang, C., S. Shindo and I. Machida, 1998: Topographical effects on the distributions of rainfall and $^{18}O$: a case in Miyake Island, Japan. *Hydrol. Proc*., Vol. 12, 673-682.

Weaver, P.L., 1972: Cloud moisture interception in the Luquillo Mountains of Puerto Rico. *Caribb. J. Sci*., Vol. 12, 129-144.

Weaver, P.L., 1995: The Colorado and dwarf forests of Puerto Rico's Luquillo Mountains. In: A.E. Lugo and C. Lowe (eds.), *Tropical Forests: Management and Ecology*. Springer, Berlin, pp. 109-141.