The wet-canopy water balance of a Costarican cloud forest

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Abstract

We quantified the following hydrological and meteorological components in a windward tropical montane cloud forest ecosystem near Monteverde, Costa Rica, during a three months field campaign in 2003: fog water deposition, precipitation, throughfall, and stemflow. Additionally we determined the stable isotope concentrations of ¹⁸O and ²H of a large number of samples from each component. Net fog water deposition was measured directly with the eddy covariance method. An average daily fog water deposition rate of 1.2 mm was measured. Fog water deposition constituted 4–7% of rainfall collected over the full period. Comparisons between direct fog water deposition measurements and the results of a mixing model using the stable isotopes as tracers revealed that the latter might be a good tool to estimate fog water deposition without an eddy covariance system in the future under many (but not all) conditions.

To compute the wet-canopy water balance, evaporation from the wet canopy was calculated with the reduced Penman-Monteith equation. For a period of 65
days, we measured 506 mm of water input (fog and rain water) and 557 mm of water output (throughfall, stemflow, and wet-canopy evaporation).

1. **Introduction**

Cloud forests are believed to add a significant amount of water to the hydrological budget of a catchment by stripping liquid fog water from the air. The quantification of this additional water input is of great importance in order to assess the hydrological importance of cloud forests for the local population. In the past, fog water inputs were quantified indirectly, with modelling approaches or with horizontal precipitation gauges. The drawback of indirect methods is that the quantification of fog water deposition is dependent on correct rainfall and net precipitation measurements. Working with horizontal precipitation gauges as the Juvik gauge (REF) leads to the problem of separating fog and rain water and translating the collected water amounts (by a vertical surface) to a horizontal surface. It is crucial to distinguish between fog and rain water inputs, because the latter are – due to their larger droplet size – deposited independent of the surface cover. Fog water deposition, however, is strongly influenced by turbulence. Because of the rougher and greater surface of forests, fog water deposition is much larger over forests than over, for example, grasslands or pasture areas (e.g. Thalmann et al. 2002). Here, the results of direct net fog water deposition measurements by the eddy covariance method are presented and compared with the results of a mixing model using the stable isotopes $^{18}$O and $^2$H as tracers. To further validate the fog water deposition measurements, we measured and calculated the remaining components of the wet-canopy water balance and compared the different approaches with each other.

2. **Experimental**
2.1 Site

Hydrological and micrometeorological measurements were performed between the 10\textsuperscript{th} of February and the 13\textsuperscript{th} of May 2003 at 1460 m a.s.l. in a small (\(XY \text{ km}^2\)) catchment near the Monteverde Cloud Forest Biological Preserve, Tilarán Range, NW Costa Rica (10°18´ N, 84°48´ W), on the windward side of the continental divide (San Gerardo Farm; national grid coordinates: \(258 – 262,\) Tilarán topographical sheet). Meteorological measurements were performed on top of a 24 m tall tower situated about 200 meters below the ridge crest of the continental divide. Hydrological measurements were performed within the same catchment, on a nearby slope, however with a different exposure (slope angle \(XY^\circ,\) exposition \(XY\)) than the one were the meteorological tower was standing (slope angle \(XY^\circ,\) exposition \(XY\)).

2.2 Methods and Instrumentation

Net fog water deposition was measured directly via the eddy covariance technique. The measurements were performed with a three-dimensional ultrasonic anemometer (model 1199 HSE with a built-in inclinometer, Gill Ltd., Solent, UK) and an active high-speed FM-100 cloud particle spectrometer (Droplet Measurement Technologies, Inc., Boulder, CO, USA). Fog droplets were continuously measured in 40 size classes between 2 and 50 \(\mu\)m diameter and were recorded together with the 3-dimensional wind speed information 12.5 times per second. For further details on the eddy covariance set-up see Burkard et al. (2003). Vertical rainfall was measured by several standard rain gauges. These precipitation measurements were corrected for aerodynamic losses following the procedure by Førland et al. (1996), and for the effects of sloping ground according to Sharon (1980). Furthermore, horizontal precipitation (i.e., fog water and wind-driven precipitation) was measured by a
modified Juvik type horizontal precipitation gauge and a self constructed, rotating gauge with a horizontal orifice (Figure 1). Throughfall was measured with the roving gauge technique using 60 totalizing rainbuckets (Lloyd and Marques 1988). Stemflow was estimated using an expert’s first guess value of 2% of throughfall because the necessary data on projected crown area of the trees were we actually measured stemflow was not yet available. Wet-canopy evaporation was calculated with the reduced Penman-Monteith equation (Monteith 1965).

In addition to the direct measurements, fog water deposition was estimated by a mixing model as described by Brunel et al. (1995), using the stable isotopes $^{18}$O and $^2$H as tracers. Samples for the determination of isotope concentrations were taken on a nominal daily basis from rain, fog, throughfall and stemflow water. Fog water was collected with a modified Caltech Active Strand Cloudwater Collector (CASCC; for details see Demoz et al. 1996). Rain water was collected with a sampler built after the description found in IAEA (2002). Throughfall and stemflow water for isotope analyses were taken as a representative subsample of the water collected by all measuring gauges. For days where samples were available from all water types, the share of fog and rain water in throughfall was calculated using the following two endmember mixing model,

$$TF \cdot \delta_{TF} = P \cdot \delta_{P} + F \cdot \delta_{F}, \quad (1)$$

where TF, P, and F are amounts of throughfall, precipitation, and fog water deposition, respectively, and $\delta$ denotes the corresponding isotopic ratio of either $^{18}$O or $^2$H.

3. Results and Discussion
3.1 Fog water deposition

Average net fog water deposition measured by the eddy covariance system for a visibility below 1000 m was 0.05 mm h\(^{-1}\) or 14.2 mg m\(^{-2}\) s\(^{-1}\). This amount is similar to the fog water deposition measured with the same equipment in a cloud forest ecosystem in Puerto Rico (0.04 mm h\(^{-1}\) or 10.2 mg m\(^{-2}\) s\(^{-1}\), Holwerda et al. 2004) and lies within the range of reported values measured outside the tropics (Beswick et al. 1991; Vong and Kowalski 1995; Vermeulen et al. 1997; Burkard et al. 2003). The daily deposition rate of 1.2 mm d\(^{-1}\) lies within the range of 0.27–6.3 mm d\(^{-1}\) of reported cloud water interception rates in tropical montane areas obtained by different indirect methods (Bruijnzeel 2001). Fog water deposition expressed as a percentage of rainfall (4%) was at the lower end of the scale reported by Bruijnzeel (2001) (2–281% of associated rainfall). While the daily deposition rates are reasonable values, the share of fog water in total water input is very small. According to the direct measurements, fog water did not add a significant portion of water to the water balance of this ecosystem during our field campaign. This can be explained by the low fog frequency that we observed. In addition to a high cloud base, the lack of fog was caused by the “temporales del pacifico” weather pattern (Clark et al. 2000). During several days, the field site was on the lee side of the continental divide due to western winds caused by this pattern. According to Clark et al. (2000), these types of weather systems occur in the hurricane season (August–October) and their occurrence in March may have led to a nonrepresentative dry season. However, Clark et al. (2000) also report 20–25% average cloud immersion of the upper slopes and ridges along the continental divide in the area of Monteverde during the dry season. This percentage compares well with the 26% of fog that we observed during our campaign. Therefore, the share of 4% of fog water deposition in precipitation that we found seems to be quite normal for the dry period.
Isotope concentrations of all water types were available for 21 days. The calculated fraction of fog water in throughfall water was outside the acceptable range of 0–100% on 7 to 8 days ($^2$H and $^{18}$O, respectively). Thus, in 33–38% of the conditions the simple mixing model of Eq. (1) failed. The fractions obtained for the remaining days are shown in Figure 2. The calculated fractions of fog water in stemflow were all outside the range of 0–100%, and the concentration of $^2$H and $^{18}$O in the evaporated water was not determined. To overcome these problems and nevertheless be able to estimate a daily fog water deposition with the mixing model approach, we therefore assumed the same fraction of fog water in throughfall, stemflow and evaporated water, and multiplied them with the respective amounts. For two days, the resulting fog water deposition was higher than 4 mm d$^{-1}$, which is unrealistically high. We therefore excluded these data from a comparison with the directly measured amounts. Figure 3 shows the comparison between the calculated fog water deposition with $^{18}$O as the tracer and the directly measured amounts. The eddy covariance net flux measurements and the rates estimated with the stable isotope tracer technique scatter nicely along the 1:1 line, except for two events. The correlations were higher for the $^{18}$O ($r = 0.72, p = 0.009$) than for the $^2$H tracer ($r = 0.54, p = 0.045$), such that we focus on the results obtained via the $^{18}$O tracer in the following. The modelled fog water deposition constituted 150% of the directly measured amount. If we now assume that our eddy covariance net fog water flux measurements are too low and should be enlarged by a factor 1.5 as we determined above, then our best estimate for fog water deposition grows to 7% of concurrent rainfall.

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### 3.2 The wet-canopy water balance

For the computation of the water balance, a period of 65 days with uninterrupted
measurements of all components was selected (9th of March – 13th of May 2003). For this period, we measured and calculated the following amounts (all in mm):

\[ 487_{\text{corrected rainfall}} + 19_{\text{fog}} \approx 497_{\text{throughfall}} + 50_{\text{wet-canopy evaporation}} + 19_{\text{stemflow}}. \]  \hspace{1cm} (2)

For these 65 days, the difference between input (rain and fog) and output (throughfall, evaporation, and stemflow) is not statistically significant (paired Wilcoxon rank sum test, 95% confidence level, \( p = 0.30 \)). However, on days with high wind speeds and flat rain angles, the mismatch between input and output is quite large (Fig. 4, days 91 and 92, 1st and 2nd of April).

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We assume that the error in throughfall measurements, which constituted 97% of the output component during these two days, was small due to the roving gauge technique (Lloyd and Marques 1988). We believe that it is most likely that the unexplained amount during these days is due to undermeasured amounts of input rather than overestimations of the output components. Moreover, it is unlikely that the greater proportion of this missing water input could be attributed to undermeasured fog water deposition. If the opposite were true, then this would require a daily deposition rate of more than 18 mm d\(^{-1}\), which appears unreasonably high compared to the range reported by Bruijnzeel (2001). In addition, the modelled fraction of fog water in throughfall is very small for large throughfall amounts (Fig. 2), indicative of the fact that fog water inputs are only significant at times when precipitation rates are comparatively low. For example, a daily throughfall amount of 9.7 mm yields a fraction of 5% of fog water in throughfall according to the mixing model (Eq. 1). The daily throughfall amount for the 1st and 2nd of April was much larger than this (165 and 134 mm, respectively). Unfortunately, there is no isotopic information available from this storm event. But according
to Figure 2 we expect that the fraction of fog water in throughfall was clearly below 5% during this event. This suggests that fog water deposition must have been below 15 mm during these two days (the eddy covariance system measured an amount of 5.5 mm). Therefore we believe that the greatest proportion of the unexplained gap of 70 mm in our water balance (Eq. 2) was due to undermeasured horizontal rainfall. This argumentation is also supported by our measurements from a home-built rotating vertical orifice gauge (Fig. 1).

The isotopic concentrations of the water collected with this vertical orifice gauge were not significantly different from the concentrations found in rain water, but there was a clear difference to the concentrations found in fog water. Therefore, the water collected by this gauge during the 1st and 2nd of April (180 and 179 mm, respectively), was rain water. The amounts measured by this gauge were higher than the throughfall amounts because they represent the amount of precipitation caught by a vertical surface and not that of the sloping ground. The true precipitation thus was certainly smaller, but the results of the vertical orifice gauge show that a conventional rain gauge plus the Sharon (1980) and Førland et al. (1996) corrections are not enough to account for the horizontal precipitation in such an environment.

**Conclusions**

For a period of 65 days, we measured and calculated the components of the wet-canopy water balance. Over the whole time period, there was no statistically significant difference between input (fog and rain water) and output (throughfall, stemflow and wet-canopy evaporation). Fog water inputs ranged between 4% (eddy covariance net flux measurements) and 7% (tracer mixing model with $^{18}$O) of incident rainfall. Rainfall was corrected for the effects of sloping ground and aerodynamical losses. The corrected amounts were 27% greater than the measured ones. For a storm event with wind driven and thus
slanted rainfall, however, the corrections were not large enough and a gauge with a vertical orifice was found to perform better. We therefore suggest to further improve rainfall measurements especially with respect to wind and terrain slope effects.

The isotope mixing model was found to be a good tool to assess the fraction of fog water in throughfall for many precipitation events. However, this method needs further refinement as several relevant questions remain still unsolved: (1) Why did the obtained fraction for almost half of the events lie outside the valid range of 0–100%? (2) Why did the method not work for stemflow samples? (3) Is there an isotopic fractionation occurring while fog water is sampled with an active strand cloud water collector? (4) How large is the effect of evaporation on the isotopic concentrations measured in throughfall water?

An enlargement of the available data with both direct net fog water deposition and isotopic composition measurements is expected to increase our confidence that the isotope mixing approach could potentially replace the expensive and sophisticated eddy covariance instrumentation. Before this is the case, we need to understand also why results obtained with the $^2$H tracer differ so much from those based on $^{18}$O.

**References**


Figure 1: The home-built rotating vertical orifice gauge.
Figure 2: Measured throughfall amounts and the respective fraction of fog water in throughfall calculated with the mixing model (Eq. 1) using $^{18}$O as tracer.
Figure 3: Directly measured eddy covariance net fog water deposition rates versus rates calculated via the mixing model with $^{18}\text{O}$ as the tracer ($r^2 = 0.52$, $p = 0.009$).
**Figure 4:** The wet-canopy water balance computed for each day. Inputs are displayed with positive values and dark bars, outputs are negative with gray bars, and the deviation from a closed budget is given by the bold line.