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Tropical Montane Cloud Forests in the Orinoco River basin: Inferring fog interception from through-fall dynamics

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ABSTRACT

The interaction between vegetation and the atmosphere is highly complex in fog affected ecosystems like Tropical Montane Cloud Forests (TMCFs). Despite acknowledging fog effects on the canopy's water balance, quantifying their influence remains challenging. While the reduction in potential evaporation that is caused by fog presence, is largely independent of land cover, fog interception itself strongly depends on the land-cover's vegetation characteristics. A better understanding of how these two fog related processes affect the water balance is highly relevant under current land-use and climate-change pressures. In this study we evaluate the different fog effects on TMCFs' canopy interception combining model simulations and high temporal resolution (10 min) observations that were collected in different TMCF regeneration stages: early succession, secondary and old-growth TMCFs. We also analyse the difficulties in closing catchment water balances caused by limitations on the interpretation of throughfall data to properly represent these fog effects.

Results show that different fog frequencies along elevation affect potential evaporation. The higher elevation old-growth TMCFs have a lower simulated evaporation and a lower dry canopy frequency than the low elevation secondary and early succession forests. Furthermore, we show that fog water inputs during fog-only events, even though higher at the higher elevation, are irrelevant as water inputs (from 0.8% to 1.6% of measured rainfall), but fog's contribution to through-fall during foggy rainfall events can be more relevant (from 5.8%–12.8% of measured rainfall). Additional to the fog trends along the elevation, we also uncover variable fog-vegetation interactions controlled by differences in canopy water storages as a function of forest cover. Each evaluated process has associated uncertainties, which together cumulatively explain why closing a water budget in TMCF catchments is limited by data collection methods that probably do not capture all relevant fog effects. In addition, this study also indicates that the temporal resolution of measured rainfall and through-fall and compensating effects of canopy parameters that are estimated by the commonly used Rutter canopy-rainfall interception model, pose an additional challenge to understand and quantify fog effects in the water budgets of TMCFs.

1. Introduction

Understanding the consequences of land-use and climate changes for hydrologic processes is a major scientific challenge (DeFries and Eshleman, 2004; Hooke et al., 2012; Wagener et al., 2010). The implications of these changes on the water cycle, and ultimately water availability at variable spatial and temporal scales, are subject to considerable debate and research (e.g. Ellison et al., 2017; Balthazar et al., 2015; Bonell, 2010; Ellison et al., 2012). Canopy interception is a relevant water-balance component that is affected by land-use change (Piao et al., 2007), and also potentially by climate change (Wallace and McJannet, 2012, 2013). Interception can strongly affect water yields (Van Dijk and Peña-Arancibia, 2012) and also precipitation through intensified land-atmosphere interactions (Guillod et al., 2014). Deforestation and subsequent forest recovery induce changes in canopy characteristics that determine the canopy's water storage and drainage rates (Holwerda et al., 2010; Ponette-González et al., 2010; Pryet et al., 2012), while changes in rainfall (P) and potential evaporation (PE) affect the input and losses of water from the canopy (Crockford and Richardson, 2000). The interaction between the vegetation and the

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atmosphere is even more complex in fog affected ecosystems like Tropical Montane Cloud Forests (TMCFs; Chu et al., 2014; Dietz et al., 2007).

Fog persistence plays a key role in modulating TMCFs' unique hydrology (Grubb, 1977). Fog affects evapotranspiration and thus plant-water relations by reducing incoming solar radiation, increasing leaf wetness frequency and decreasing atmospheric vapour pressure deficit (Letts and Mulligan, 2005; Reinhardt and Smith, 2008; Eller et al., 2015). Reduced transpiration results in less water uptake from the soils and reduced canopy evaporation can increase through-fall, both sustaining higher moisture conditions in the system. Furthermore, fog interception by the canopy provides an additional water input to rainfall (Zadroga, 1981) and potentially induce foliar water uptake (Eller et al., 2015; Goldsmith et al., 2013). The previously described fog effects on TMCFs' hydrology suggest that TMCFs play a key role in regulating streamflows (e.g. Roa-García et al., 2011; Ramírez et al., 2017b). Despite their hydrological relevance, TMCFs are vulnerable to land-use and climate changes (Scatena et al., 2011). On the one hand, land-use change poses a major threat as more than half of TMCFs world-wide were converted to other land use types by the year 2000 (Mulligan, 2011). On the other hand, climate change can alter the elevation at which fog occurs exposing TMCFs to drier atmospheric conditions (Still et al., 1999).

Although the effect of fog on the canopy water balance is acknowledged, quantifying its influence remains challenging (Frumau et al., 2011). Indirect approaches, such as identifying thresholds of meteorological variables to infer fog's contribution to through-fall has been possible for drier environments with a clear meteorological signature (e.g. Marzol, 2008) but not so for extremely wet environments where fog does not have a clear meteorological signature (e.g. Brauman et al., 2010). Also, several direct measurement methods have been employed to quantify fog's liquid water content including passive or active fog collectors, fog detectors and fog/cloud droplet spectrometers. However, they all have their caveats concerning, for example, the discrimination between fog and wind-driven rainfall, minimum water content thresholds and fog droplet size distribution. These caveats are discussed in detail by Bruijnzeel et al. (2006). Additionally, these methods are point measurements and this limits their spatial representativeness. Furthermore, quantifying fog's liquid water content alone is insufficient to determine the canopy's fog interception rates. The fog-vegetation interaction also depends on wind speed and vegetation characteristics, like canopy roughness and canopy leaf area, leaf surface texture (e.g. hydrophilic hairs or hydrophobic waxes), leaf inclination and exposition to wind direction (Crockford and Richardson, 2000; Herwitz, 1985). To our knowledge only a few studies focusing on relatively few species (< 13 spp) have considered most of the above mentioned canopy characteristics (e.g. Holder and Gibbes, 2017; Garcia-Estringana et al., 2010). The required information on canopy characteristics is already overwhelming, but determining all these features is impossible in montane (> 1000 m asl) tropical forest contexts, where plant diversity can reach up to 100 spp per 0.1 ha (Gentry, 1988). A more practical approach is to evaluate the fog/vegetation interaction at the catchment scale with effective parameters that represent the high spatial variability within the canopy.

A common approach to study fog and canopy interactions is to compare interception and through-fall (hereafter TF) between areas or seasons with contrasting fog influence, and/or between different land-cover types (e.g. Brauman et al., 2010; Giambelluca et al., 2011; Ponette-González et al., 2010; Pryet et al., 2012). To quantify interception, precipitation above and below the canopy (i.e. TF) is measured. These comparisons allow to quantify the additional water input by fog reflected in additional TF. However, given the high temporal variability of fog occurrence at daily or shorter timescales, this quantification is likely sensitive to the temporal resolution of the measurements, which varies considerably throughout the literature (e.g. weekly: Gómez-Peralta et al., 2008; Fleischbein et al., 2005; Wullaert et al., 2009; daily: Hölscher et al., 2004; and 10 min: Holwerda et al., 2010). Furthermore, the rainfall-through-fall approach does not provide information on the relative contribution of the multiple processes affected by fog that control the canopy water balance. For example, evaporation varies between very high levels for clear sky conditions to very low levels under cloud/fog influence (Hidalgo et al., 2005), leading to contrasting canopy drying times. At the same time, the canopy water storage can also be filled by fog interception. These interactions between fog and the canopy water balance remain difficult to quantify.

Fog incidence depends mostly on upwind and local hydro-meteorological conditions. Thus, the expected climate changes regarding the length and severity of dry and wet seasons for the region (Magrin et al., 2014) can potentially alter fog formation. In contrast, fog interception by the vegetation depends on vegetation characteristics associated with land cover (e.g. Holwerda et al., 2010). Therefore, under current land-use and climate change pressures it is highly relevant to better understand how the two processes of reduced evaporation and fog interception affect the water balance of ecosystems, such as TMCFs.

Canopy interception models allow to integrate the through-fall/rainfall (TF/P) processes by considering rainfall, evaporation, drainage outputs and canopy characteristics. Muzylo et al. (2009) review canopy interception models and their use worldwide. The two most commonly used interception models are the Rutter model (Rutter et al., 1971, 1975; Rutter and Morton, 1977) and the Gash model (Gash, 1979). The Rutter model is a process-based continuous water-balance model with two empirical drainage parameters. The Gash model is the analytical version of the Rutter model with reduced data requirements and it is thus more widely used (Muzylo et al., 2009). The Gash model partitions individual rainfall events into three stages: wetting up, saturation and evaporation after rainfall ceases, but it requires the discretization of rainfall events assuming to have a dry canopy preceding each event. The validity of this assumption is questionable in fog affected forests where fog is not detected by rain gauges. The continuous Rutter model does not rely on the assumption of a dry canopy. Furthermore, the continuous water-balance calculation provides insights in the water stored in the canopy in-between rainfall events and this allows to determine the dry/wet canopy frequency. Hence, the Rutter model is best suited to integrate meteorological data with TF data to understand the fog effect on the canopy water balance in TMCFs.

In this study, we aim to estimate the multiple fog effects on the canopy water budget in three successional TMCF stages. Our analyses are based on TF and meteorological data coupled with canopy interception modelling. To achieve our aim we will address the following research questions (RQs; see also Fig. 1):

RQ1. How does the temporal resolution of measured rainfall and through-fall affect the estimates of additional water inputs by fog?

RQ2. What is the potential effect of different fog intensities on evaporation and how does this affect the partitioning of rainfall between through-fall and evaporation for the three main forest covers in our study area?

RQ3. How (seasonally) relevant are the fog water inputs during fog-only events in the three main forest covers in our study area?

RQ4. What is the fog effect on through-fall during rainfall in the three main forest covers?

To answer the research questions we monitored at a 10 min time resolution for more than a year, three neighbouring catchments located within the Colombian Orinoco River basin with different land covers: old-growth TMCF (OGF), secondary (SECF) and early successional stages (EARF) and grasslands. Previous studies on these catchments have shown that there are missing sources of water to close the water budgets (Ramírez et al., 2017a). A positive correlation between fog/