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The performance of three fog gauges under field conditions and its relationship with meteorological variables in an exposed site in Tenerife (Canary Islands)

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ABSTRACT

We characterized the fog phenomena and associated micrometeorological variables in a 1093 m a.s.l. site in Tenerife (Canary Islands) during a 42 months period with three different fog gauges. Fog was more frequent during night-time and early morning, concomitantly with a reduction in ambient temperature and an increase in wind velocity (u). Furthermore, diurnal hourly medians of both reference evapotranspiration ($r^2 \geq 0.75$) and net radiation ($r^2 \geq 0.95$) were linearly correlated during foggy versus fog free conditions. Such correlations were different depending on whether fog was light (i.e. visibility, $\Omega > 200$ m) or dense ($\Omega < 200$ m). Although the actual gauge's fog water collection (*FWC*) depends on many concurrent factors and it is nonlinearly related to the micrometeorological variables, thus difficult to predict, the curves fitting the maxima of *FWC* vs. Ω and *FWC* vs. u data were shown to be a good descriptor of the fog water collection potential of the site. Some bounds were established on such envelope curves during strong wind gusts in terms of the force balance that lead to re-entrainment and clogging of a particular gauge screen by water drops with different geometry. The results presented advance on the possibility of relating ground base local measurements of fog water yield with the remote monitoring of auxiliary meteorological variables, such as the visibility, in order to characterize broad areas for their fog water harvesting potential, either for its exploitation or its effect on cloud immersed forests.

1. Introduction

Fog may represent a water input in cloud-immersed ecosystems, but may also be of practical use for human activities such as reforestation or agriculture in areas with low precipitation (Klemm et al., 2012). Thus characterization of fog water availability is of wide interest. Apart from its potential role as water/nutrients supplier in forest soils, by droplet deposition or impaction and subsequent dripping from the vegetation (Ingraham and Matthews, 1988; Bruijnzeel and Proctor, 1995; Beiderwieden et al., 2007; Ritter et al., 2008), fog reduces incoming radiation, temperature and vapor pressure deficit, thus providing a microenvironment of reduced evapotranspiration (Giambelluca and Nullet, 1991; Gu et al., 2002; Eugster et al., 2006; Ritter et al., 2008). Diminished tree transpiration during fog events has been in fact confirmed using sap flow sensors (Hutley et al., 1997; Hildebrandt et al., 2007; Ritter et al., 2009; Alvarado-Barrientos et al., 2014). This technique has also permitted to verify the direct incorporation into vegetative tissues of fog water droplets deposited onto leaves. Thus fog may alleviate water scarcity during drought periods by decoupling the plant from the soil (Simonin et al., 2009; Eller et al., 2013). It has been also suggested that, under the conditions prevailing during cloud immersion, diffused light may be more appropriate for photosynthesis and thus carbon sequestration by plants may be enhanced by fog (Johnson and Smith, 2006; Still et al., 2009).

Fog water contribution may be evaluated by different techniques: throughfall gauges (Ritter and Regalado, 2010; Zimmermann and Zimmermann, 2014); eddy covariance systems and isotopic analysis of fog water (Vermeulen et al., 1997; Fischer and Still, 2007; Schmid et al., 2011; Scholl et al., 2011; Goldsmith et al., 2012); or micrometeorological measurements combined with mathematical modeling (Klemm et al., 2005; Eugster et al., 2006; Katata et al., 2008; Katata, 2014). Despite the availability of such a variety of techniques, many hydrological projects aiming to quantify fog either for chemical analysis or for estimating its water contribution employ artificial fog catchers. Such a widespread use

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of fog gauges may be due to their low maintenance requirements, and simple characterization of the fog dynamics with a single low-tech instrument. Although these may only provide an approximation of the potential fog water dripping from the canopy, if appropriately calibrated, they may also serve as a way to estimate the actual fog precipitation (Ritter et al., 2008; Katata et al., 2010). Nevertheless it would be desirable to relate the local fog water yields with some other meteorological variables, such as the air relative humidity, wind velocity, the fog liquid water content (*LWC*) and/or visibility, amenable for continuous monitoring. In this respect the results presented by Eugster et al. (2006) indicate that the fog water input fluxes in a Puerto Rican cloud forest, determined using an eddy covariance system, may be described in terms of other ancillary meteorological variables, such as the visibility. Furthermore, the visibility is rather easier to measure than the liquid water content or the droplet size distribution of the cloud, and thus this is readily available for continuous monitoring, either on the ground or retrieved from satellite data. Continuous measurements of *LWC* and fog droplet size distributions in the Canary Islands are merely anecdotal (Taima-Hernández et al., 2012), and it would be almost inconceivable to carry out these in other remote areas with limited resources.

Passive fog gauges generally consist on one or several screens of either vertical parallel filaments or a cross-linked open fabric where wind-driven fog water droplets first impact, then coalesce and finally drain to be collected below. Various geometries, from the simplest rectangular display to cylindrical or polyhedral shapes, have been tested in the field. The effective collection surface is usually of only a few square meters (0.5–10 m^2) and the water yields range from 0.2 up to 4 $L\,m^{-2}\,d^{-1}$ (Table 1 in Bruijnzeel and Proctor, 1995). However a systematic comparison of different passive fog gauges designs remains insufficient. Goodman (1985) evaluated the fog water efficiency of a wire harp and a cylindrical collector built with three concentric layers of vertically strung wires operating simultaneously in Montara Mountain (San Francisco) during the summer of 1982. Frumau et al. (2011) related the water yields of a wire harp screen, a modified Juvik-type cylindrical gauge and a tunnel (Daube-type) gauge in a windward cloud forest site in northern Costa Rica. Holwerda et al. (2011) compared the performance of a wire harp, a modified standard fog gauge and a Juvik-type cylindrical gauge during a two months period in a Puerto Rican elfin cloud forest. In the same island (Tenerife) as the current study, Santana-Pérez carried out one of the most extensive studies about the fog water phenomena after those pioneered by Kämmer (1974). Santana-Pérez (n.d.) reported fog water values collected with both cylindrical and rectangular galvanized mesh (1.5 × 1.5 mm^2 voids and 0.5 mm wire section) fog gauges between 1050 and 1600 m a.s.l. during 1985 (see also Santana-Pérez, 1986).

Apart from these rather limited studies, to our knowledge no further work has been accomplished in order to investigate suitable correlations between various fog water measurement techniques worldwide. This limits the possibility of relating fog water yields reported across the bibliography with different fog gauges objectively. Part of this limitation lies on the fact that a full characterization of the impacting, aerodynamic, clogging and droplet re-entrainment phenomena that take place during the collection of fog water droplets by artificial structures has not been established yet, and thus the fog water volumes collected by different devices are usually interpreted empirically. This may explain, for instance, why the ~66% efficiency predicted from liquid water content measurements carried out in front and behind a large double-layer Raschel mesh fog catcher was not confirmed by the water output yielded, rendering an actual 2.9 lower gauge's efficiency of about 20% (Schemenauer and Joe, 1989). Larger deviations from the theoretical efficiency values have been reported for bigger fog droplets and higher *LWC* (Wieprecht et al., 2005). Consequently, some of these differences between actual and theoretical efficiency were attributed to losses of larger fog droplets due to interior wall effects in the collecting device or airflow conditions at the inlet (Wieprecht et al., 2005; Michna et al., 2013) and re-entrainment of collected drops back into the wind stream (Park et al., 2013). Wind drag forces grow with the square of the collected drop radius (r_{drop}) while forces of adhesion are linearly dependent on r_{drop}, thus larger water drops are more prone to re-entrainment (Park et al., 2013).

Several previous studies have considered the fog collection mechanism from a theoretical point of view. Demoz et al. (1996), based on earlier work by Davidson and Friedlander (1978), studied the fog droplet impaction efficiency of the bank of filament strands in an active Caltech collector. Rivera (2011) investigated theoretically the aerodynamic efficiency of Raschel type meshes. Saturation of a mesh by impinged drops leads to clogging and therefore this becomes less permeable to air, thus reducing its aerodynamic efficiency. By contrast weak adhesion of water drops onto the impacting filaments may provoke detachment by strong wind gusts and re-entrainment back into the wind stream. Park et al. (2013) characterized mathematically the mesh clogging and droplet re-entrainment mechanisms, thus extending the earlier work by Rivera (2011). Finally, Regalado and Ritter (2016) recently reviewed the models describing the impaction and aerodynamic efficiencies of multilayer screens of staggered filaments, concluding that the aerodynamics rather than the impaction is the limiting process for maximizing fog water collection.

The current study was carried out in the north side of Tenerife (Canary Islands) at 1093 m a.s.l. The vertical thermic structure of the atmosphere over this region of the Atlantic is a consequence of the atmospheric subsidence associated with the descending branch of the general circulation northern Hadley cell (Carrillo et al., 2015). Such a temperature inversion, and the orographic lifting of moist air masses driven by the trade winds towards the western islands, is responsible for the establishment of a stable stratocumulus layer between 900 and 1500 m a.s.l. and the consequent presence of frequent fogs in the Macaronesia (Font Tullot, 1956).

The objective of this study is to compare fog water captured by three fog gauges with different geometries and impacting configurations, characterize the concomitant meteorological variables during fog-free versus fog-only events and interpret the results in terms of some of the physical mechanisms that take place during the collection process.

2. Materials and methods

2.1. Study site

The study site is located in La Esperanza (El Rosario, Tenerife) at an altitude of 1093 m a.s.l. (28°26′37.82″N, 16°22′40.27″W; X: 365 078 m Y: 3 147 143 m; 28N R zone; WGS84). The orientation is N–NW with affection by frequent fogs.

2.2. Instrumentation

The study spanned from 1st July, 2012 until 31st December, 2015. The instrumentation was placed on top of a regulatory drinking water closed reservoir. This comprised a micrometeorological station and several fog water gauges. The following variables were monitored at one minute intervals and stored as averages or cumulative totals every 15 min using a Combilog datalogger (Up GmbH, Cottbus, Germany): temperature and relative humidity (HMP45C thermo-hygrometer, Campbell Scientific Ltd, Lougborough, UK), global radiation (SKS 1110 pyranometer, Skye Instruments Ltd, Powys, UK), mean and maximum wind speed (A100R anemometer, Campbell Scientific Ltd), wind direction (W200P wind vane,