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ScienceDirect
Agricultural and Forest Meteorology 139 (2006) 288–306
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Characteristics of fog and fogwater fluxes in a Puerto Rican elfin cloud forest

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Received 19 October 2005; received in revised form 15 June 2006; accepted 10 July 2006

Abstract

The Luquillo Mountains of northeastern Puerto Rico harbours important fractions of tropical montane cloud forests. Although it is well known that the frequent occurrence of dense fog is a common climatic characteristic of cloud forests around the world, it is poorly understood how fog processes shape and influence these ecosystems. Our study focuses on the physical characteristics of fog and quantifies the fogwater input to elfin cloud forest using direct eddy covariance net flux measurements during a 43-day period in 2002. We used an ultrasonic anemometer–thermometer in combination with a size-resolving cloud droplet spectrometer capable of providing number counts in 40 droplet size classes at a rate of 12.5 times per second. Fog occurred during 85% of the time, and dense fog with a visibility < 200 m persisted during 74% of the period. Fog droplet size depended linearly on liquid water content ($r^2 = 0.89$) with a volume-weighted mean diameter of 13.8 μm. Due to the high frequency of occurrence of fog the total fogwater deposition measured with the eddy covariance method and corrected for condensation and advection effects in the persistent upslope air flow, averaged 4.36 mm day^{-1}, rainfall during the same period was 28 mm day^{-1}. Thus, our estimates of the contribution of fogwater to the hydrological budget of elfin cloud forests is considerable and higher than in any other location for which comparable data exist but still not a very large component in the hydrological budget. For estimating fogwater fluxes for locations without detailed information about fog droplet distributions we provide simple empirical relationships using visibility data.

Keywords: Fog; Rain; Elfin cloud forest; Humid tropics; Eddy covariance; Flux measurements; Deposition

1. Introduction

The frequent occurrence of dense fog is a common climatic characteristics of so-called cloud forests around the world (Hamilton et al., 1995). However, the way fog shapes and influences cloud forest ecosystems is poorly understood (Bruijnzeel and Veneklaas, 1998). Compared with montane rain forests below the cloud belt, cloud forests tend to be mossier (Frahm and Gradstein, 1991), shorter-statured and more xerophyllous (Grubb, 1977). All of these characteristics are generally thought to be influenced by the frequent occurrence of fog although it is still not fully understood

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doi:10.1016/j.agrformet.2006.07.008

how and to what extent fog achieves this (Bruijnzeel and Veneklaas, 1998). Several decades ago, the German geobotanist Heinrich Walter expressed his doubts as to whether fog really is the dominant environmental factor in structuring cloud forest ecosystem as a whole, or only is important for the survival of certain types of epiphytes and mosses on trees (Walter, 1973). In recent decades, the hydrological importance of fog deposition as a source of sustained dry season base flows from cloud forested headwater areas has been emphasized repeatedly (Zadroga, 1981; Brown et al., 1996; Bruijnzeel, 2001).

The process of fogwater deposition is driven by impaction and interception of cloud droplets by the vegetation. Cloud droplets in fog follow the turbulent motion of the air in which they are dispersed (see La Porta et al., 2001; Voth et al., 2002). As soon as they touch the surface of a plant leaf, a stem of a tree, or any other obstacle they are intercepted and form a thin film on that obstacle. If the contact is more violent, the more correct term is impaction, with the same result that the droplet becomes incorporated into the water film of the wet canopy. Using the eddy covariance method we quantified the resulting ecosystem-scale fogwater deposition. Our results suggest that measured fog characteristics and deposition rates in a wet tropical montane elfin cloud forest are important for the hydrological budget. However, as long as there is abundant rainfall the additional input by fogwater deposition cannot be considered a very large budget component in terms of its amount. We therefore suggest to focus rather on the timing and duration of fog (affecting tree physiological functioning, including the light climate and soil water uptake), and on its role as a source of dissolved nutrients in generally nutrient-poor tropical mountain ecosystems (cf. Hafkenscheid, 2000).

Mountainous areas are among the most diverse ecosystems on Earth (Orme et al., 2005) and tropical mountain cloud forests are known for their high share of endemic plants and animals (Bruijnzeel, 2001; Leo, 1995; Kappelle and Brown, 2001). Cloud forests have been reported to be very susceptible to changes in environmental conditions (Lawton et al., 2001; Pounds et al., 1999, 2006). The conservation of the remaining tropical mountain cloud forests is therefore one of the primary goals of the UNEP Cloud Forest Agenda (Bubb et al., 2004).

Within the Long-Term Ecological Research (LTER) network of the U.S.A., the Puerto Rican Caribbean National Forest in the eastern Luquillo Mountains harbours important fractions of tropical montane cloud forests, both of the montane and elfin cloud forest type (Bruijnzeel, 2001) on its upper most peaks. Scientific investigations in the elfin cloud forest began as early as the late 1960s (Baynton, 1968, 1969; Brown et al., 1983). The area became part of the LTER network in 1988 and observations are still ongoing (http://luq.lternet.edu). Here we report the first direct measurements of fog droplet distributions and their turbulent exchange with the forest canopy conducted in any tropical montane cloud forests of the world. Since our results compare well with measurements from other mountain areas outside of the tropical zone, we provide more generally valid recommendations on how to empirically estimate fogwater deposition based on easily measured variables such as horizontal visibility.

2. Materials and methods

Fog is not definied equally by all scientific disciplines or researchers. Here we adhere to the following definition: fog occurs if the horizontal visibility is less than 1000 m (this is the most common meteorological definition according to Glickman, 2000), and the cloud droplets in the air reducing the visibility are less than 200 μm in size (an extension advanced by Glickman, 2000). The first criterion was determined in the present study with a forward-scattering instrument (Section 2.2.3), the second criterion was based on measurements made with a high-speed cloud droplet spectrometer (Section 2.2.1). All statistical analyses were performed with R version 2.0.0 (R Development Core Team, 2005).

2.1. Site description

Our measurements took place near Pico del Este (65°45′39″W,18°16′17″N, 1015 m a.s.l.) in the Luquillo Experimental Forest (LEF), in the northeastern part of Puerto Rico. Measurements were made ≈100 m below the crestline of a 17° slope of east-northeasterly aspect directly facing the prevailing winds (Brown et al., 1983; see also map shown in Fig. 1). Accordingly, the site is strongly influenced by the northeasterly trade winds (Garcia-Martino et al., 1996). Furthermore, occurrence of fog is very frequent due to the forced lifting and cooling of humid air masses arriving from the Atlantic Ocean (Baynton, 1969; Holwerda et al., 2006). Over the roughly 20 km transect from the Atlantic coast to the site there is a dramatic change in forest types, ranging from subtropical dry forest near the coast through lower montane rain forest (Tabonuco) to montane palm brakes, upper montane rain forest (Colorado), and elfin cloud forest (Brown et al., 1983). The vegetation at Pico del