Fog in the Andean Páramo: measurements, dynamics, and its influence on soil hydrology and evapotranspiration processes

Gina Marcela Berrones Guapulema

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UTPL

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Fog in the Andean Páramo: measurements, dynamics, and its influence on soil hydrology and evapotranspiration processes

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Autora:
Gina Marcela Berrones Guapulema
CI: 0603012329
Correo electrónico: ginaberrones@gmail.com

Director:
Dr. Rolando Enrique Célleri Alvear
CI: 0602794406

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Resumen

El páramo se caracteriza por poseer un clima muy húmedo, así como la continua presencia de neblina y lluvias de baja intensidad. La característica más importante del páramo es su alta capacidad de regulación del agua que en parte podría estar relacionada con la alta frecuencia de neblina y lluvias de baja intensidad (llovizna). Por lo tanto es fundamental comprender los procesos hidrológicos que están vinculados a la ecología del páramo. Este estudio tuvo los siguientes objetivos: (1) cuantificar la neblina capturada de tres tipos diferentes de colectores y comprender su dinámica e importancia en la precipitación anual; (2) determinar en qué medida la deposición de la neblina contribuye a la humedad del suelo; y (3) analizar el impacto que genera la neblina en las tasas de evapotranspiración, en diferentes condiciones (despejado, nublado y lluvioso). Los hallazgos de este estudio muestran que la neblina ocurre a muy bajas intensidades (0.2 mm h^{-1}) reportándose eventos de corta duración (<3 horas) a velocidades de viento inferiores a 4 m s^{-1}. La mayoría del tiempo la neblina aparece combinada con otro tipo de precipitación (llovizna, lluvia ligera o lluvia) y la neblina tiende a ser más intensa en la madrugada y en la noche. En promedio, la neblina diaria es aproximadamente 1.37 mm. En general, la neblina y la llovizna son las principales fuentes de agua para la vegetación del páramo, especialmente durante las últimas horas de la noche y las primeras horas de la mañana, cuando la evaporación es baja. La deposición de agua de neblina muestra que solo el 4,5% de ésta llega al suelo, contribuyendo a cambios de humedad del suelo bastante bajos (0.1-0.2 mm), mientras que la combinación de neblina con lluvia de baja intensidad genera una mayor contribución a la humedad del suelo (hasta 4.3 mm). Estos eventos son potencialmente importantes tanto para la humedad del suelo como para el caudal, debido a su larga duración y alta cantidad total por evento. Las tasas de evapotranspiración diaria se reducen en un 43% debido a la presencia de neblina + lluvia de baja intensidad, en comparación con condiciones despejadas (sin neblina y sin lluvia). La radiación neta se reduce en un 9,2% durante condiciones de solo neblina, principalmente porque su ocurrencia en las primeras horas de la mañana es mayor, y cuando la radiación solar alcanza su máximo valor, la ocurrencia de neblina es menor. Mientras que, durante condiciones mixtas, la radiación neta se reduce en un 33%. Durante la ocurrencia de períodos menos húmedos, la evapotranspiración también fue baja, lo que sugiere que la presencia de neblina y llovizna puede inhibir la transpiración, limitando la pérdida de agua por evaporación y también podría aliviar el estrés hídrico.

Palabras clave: Neblina. Páramo andino. Lluvia de baja intensidad. Pajonales. Evapotranspiración. Humedad del suelo.

Abstract

The páramo ecosystem is characterized by a very moist climate and the continuous presence of fog and low-intensity rainfall. The most important páramo feature is the high water regulation capacity which in part might be related to the high frequency of fog and low-intensity rainfall (drizzle). Therefore, it is essential to understand the hydrological processes that are linked to the ecology of the páramo. This study aimed the following three objectives: (1) to assess fog water estimates derived from three different types of fog gauges, and from them to understand its temporal dynamics and the importance of fog to annual rainfall; (2) to quantify the contribution of fog water deposition to soil moisture; and (3) to analyze the impact of fog on evapotranspiration rates, under different weather conditions (clear, foggy and rainy). Findings of this study show that fog occurs at very low intensities (0.2 mm h^{-1}) reporting events of short term (<3 hours) at wind velocities below 4 m s^{-1}. Most of the time fog appears combined with other type of precipitation (i.e. drizzle, light rain or rain) with fog tending to be more intense in the early morning, and at night. On average, daily fog amounts 1.37 mm. Overall, fog and drizzle are the major water sources to páramo vegetation, especially during late night-time and early mornings, when evaporation is low. The fog water deposition shows that only 4.5% of fog reaches the soil, contributing to soil moisture changes rather low (0.1-0.2 mm), whilst the combination of fog with low-intensity rainfall generate a higher contribution on soil moisture (as high as 4.3 mm). These events are potentially important for both soil moisture and stream flow, because of their long duration and high total amount per-event. Daily evapotranspiration rates are reduced by 43% due to the presence of mixed conditions (fog + low-intensity rainfall) compared with clear conditions (no fog and no rainfall). The net radiation is reduced by 9.2% during foggy conditions (only fog) mainly because its early morning hours occurrence is higher, and when solar radiation peaks fog occurrence is lower. While, during mixed conditions the net radiation is reduced by 33%. At the same time as less humid periods were reported, evapotranspiration was also low; suggesting that fog and drizzle presence can inhibit transpiration, limit water loss by evaporation and also could alleviate water stress.

Keywords: Fog. Andean páramo. Low-intensity rainfall. Tussock grasses. Evapotranspiration. Soil moisture.

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Gina Marcela Berrones Guapulema
C.I: 0603012329

Director:

Prof. Dr. Rolando Célleri Alvear

Department of Water Resources and Environmental Sciences

University of Cuenca

Co-director:

Prof. Dr. Patricio Crespo Sánchez

Department of Water Resources and Environmental Sciences

University of Cuenca

Jury committee:

Prof. Dr. Luis Timbe, University of Cuenca

Prof. Dr. Ruben Basantes, University Regional Amazónica Ikiam

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Prof. Dr. María Augusta Hermida Palacios

Gina Marcela Berrones Guapulema

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Faculty:

Faculty of Engineering, University of Cuenca.

Department:

Department of Water Resources and Environmental Sciences, University of Cuenca.

Universities:

Universidad de Cuenca, Escuela Politécnica Nacional y Universidad Técnica Particular de Loja.

City:

Cuenca, Ecuador.

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“Don't be afraid of hard work. Nothing worthwhile comes easily. Don't let others discourage you or tell you that you can't do it.”

Gertrude B. Elion

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Chapter 1

1 Introduction

1.1 Importance of the study

Mountainous ecosystems are of significant hydrological importance, providing essential and reliable water related services for downstream communities (Viviroli & Weingartner, 2004; Viviroli et al., 2007). They are important sources of freshwater, forest, energy, hydroelectrical power generation, cloud and fog formation (Beniston, 2003; Gultepe, 2015), but at the same time they are fragile and vulnerable (Schreier, 2017), since mountains represent unique areas for the detection of climatic change and the assessment of climate-related impacts (Beniston, 2003). Moreover, considering that mountains are the geographical source for more than half of the globe's rivers, the impact of climatic change on the mountain hydrology might have critical consequences in the lowland regions that rely on its water resources (Beniston, 2003). The Andes are the most important mountain range in the Southern Hemisphere (Garreaud, 2009); as this region is characterized by a variety of ecosystems related with their climate, potential climate change impacts could affect the water security for human populations (Espinoza et al., 2020). In addition, the Andes exhibit a large variety of hydrological regimes which are influenced by climatological conditions (Arias et al., 2021); therefore, it is crucial to understand the atmospheric dynamics and precipitation variability that could generate impact on the regional water resources.

The Andes encompasses different ecosystems represented by distinctive characteristics among them such as vegetation, elevation ranges, temperature, and precipitation regimes (Anderson et al., 2011). At higher elevations are the montane grasslands that include the páramos (Wright et al., 2017). These ecosystems are broadly important by their ecological and hydrological functions (Mosquera et al., 2021a). They are home of distinct plant communities, dominated by tussock grasses and cushion plants with forest patches (*Polylepis* sp.) growing along water streams. Páramos lie above the tree line and below the perpetual snow line, at altitudes ranging from about 3,000 to 4,500 m.a.s.l., (Aparecido et al., 2018) and from 11° N and 9° S along the Americas continental divide (Helmer et al., 2019). They are characterized by cold temperatures and a positive water balance caused by high rates of cloud cover and horizontal precipitation (Young et al., 2011). The low-intensity rainfall such as drizzle and fog could play an essential role on the ecosystem water cycle.

Indeed, the páramo experiences a persistent low-intensity rainfall (mainly in form of drizzle) and fog regime (Padrón et al., 2015), with fog occurring often during fast weather change conditions related to temperature, moisture, and cooling rates (Gultepe, 2015). Moreover, páramos have been recognized for their importance in supplying water for local communities (Célleri & Feyen, 2009). Here, the hydrological processes are vitally important to serve the water needs of communities in the surrounding areas (Minaya et al., 2016); thereby, rainfall and fog result crucial for freshwater sustainability (Wilson & Barros, 2014).

Precipitation in the wet páramos is fairly uniformly distributed with minor seasonal differences during the year (Célleri et al., 2007; Célleri & Feyen, 2009). Despite the scarcity of operational precipitation monitoring in these highlands in the Andes, mainly due to the complexity of the topography (Orellana-Alvear et al., 2017), most of the studies on precipitation have focused on rainfall and there is much less information about fog. For example, the rainfall spatio-temporal variability (Campozano et al., 2016; Célleri et al., 2007; Junquas et al., 2022), the analysis of rainfall-event types including relations derived from drop size distribution (Orellana-Alvear et al., 2017; Urgilés et al., 2021), rainfall estimations for modeling (Muñoz et al., 2016; Sucozhañay & Célleri, 2018), and flood warning forecast (Muñoz et al., 2021). To our knowledge, only two studies have attempted to investigate low-intensity rainfall in páramo. For example, Padrón et al. (2015) not only focused on daily and subdaily rainfall variability, but also on quantifying drizzle and determining its importance. In the same way, Cárdenas et al. (2017) quantified inputs of occult precipitation (drizzle + fog). However, much less is known about the quantification of fog separately from other precipitation types; much uncertainty still exists about its role on the páramo water resources.

Inputs from fog and cloud water can be a significant source of water in several ecosystems (Bruijnzeel et al., 2005). What is known about the hydrological role of fog in the Andes is largely derived from studies conducted in cloud forests (Ataroff & Rada, 2000; Bendix et al., 2004; Bendix et al., 2008; Bittencourt et al., 2019; Fleischbein et al., 2006; Gomez-Peralta et al., 2008; Tobón, 2021; Ramírez et al., 2017; Ramírez et al., 2018; Rollenbeck et al., 2011; Villegas et al., 2007), while in the páramo there is little published information on fog estimations. For example, previous studies focused on the comparison of the fog water intercepted by endemic vegetation with fog inputs recorded by passive fog collectors (Tobón & Gil Morales, 2007), whilst other focused mainly on horizontal precipitation, as well as its temporal and spatial distribution (Cárdenas et al., 2017). Therefore, detailed studies on the relative importance of fog to total water inputs, and on the complex interactions between the atmosphere and water-soil-vegetation are of major importance. Hence, a precise quantification of fog is essential to assess the hydrological importance of this water input.

The process of fog water deposition is driven by impaction and interception of cloud droplets by the vegetation (Eugster et al., 2006). Several studies have been based on various methods to estimate the amount of fog intercepted by vegetation, including measurements of water collected by passive fog gauges (Frumau et al., 2011; Holwerda et al., 2011; Regalado & Ritter, 2017), net precipitation measurements (Domínguez et al., 2017; García-Santos & Bruijnzeel, 2011; Gomez-Peralta et al., 2008; Holwerda et al., 2010; Pryet et al., 2012), modeling of fog water deposition (Katata, 2014; Katata et al., 2010), and the eddy-covariance method (Beiderwieden et al., 2008; Eugster et al., 2001; Holwerda et al., 2006; Schmid et al., 2011).

Considering the particular climatic conditions of the páramo such as high relative humidity, high solar radiation, low temperatures, and variations in wind speed and wind direction; the monitoring equipment to measure the low-intensity rainfall results critical to obtain accurate estimations. Moreover, fog may be more susceptible to wind than rainfall. Regardless the type of fog gauge, measurements exhibit difficulties not only to distinguish rainfall from fog, but also because some of the gauges are affected by wind direction (Giambelluca et al., 2011a). Consequently, due to the continuous presence of drizzle in the páramo the main drawback in quantifying fog deals with the complexity of distinguishing between fog and low-intensity rainfall. What is not yet clear is the impact of using different monitoring techniques on fog estimations under páramo conditions. Because of the diversity of applications for these gauges, the variety of ways in which they operate, and the configurations to assemble the most appropriate structures that minimize wind-driven rainfall, it is important to determine the efficiency of the gauges. To date, there has been no evidence of studies that compare the performances of different types of fog gauges in the páramo.

The correct quantification of fog enables the understanding of its role in the hydrological cycle. Moreover, fog is a complex phenomenon that influences the microclimate, light availability, the water budget and consequently plant functioning (Bittencourt et al., 2019; Bruijnzeel et al., 2005). Liquid water droplets from fog are transported by turbulence and they are deposited on the plant canopies (Delay & Giambelluca, 2011; Katata, 2014), dripping to the ground which can contribute to soil water. This fog input could keep the soil layers near the ground surface wet, which is important for effective water uptake by plant roots (Katata et al., 2010). It is now well established that fog deposition influences on atmosphere-land interactions such as evapotranspiration, energy budget, and water input (Katata, 2014). Despite its acknowledged importance, the existing literature on fog interactions with vegetation such as tussock grasses has been conducted in New Zealand; Campbell & Murray (1990) and Mager et al. (2016) have investigated fog as component of the water balance, while the contribution of fog deposition to water yield has been investigated by Davie et al. (2006); Holdsworth & Mark (1990); Ingraham et al. (2008). Moreover, in the Colombian páramo only Tobón & Gil Morales (2007) and Tobón & Barrero (2010) used an experimental approach to quantify fog by different types of páramo vegetation, including tussocks grasses and *Espeletia* branches. Although very few studies in the páramo have recognized the importance of fog, research has yet to systematically investigate its influence on ecohydrological processes.

In this context, this dissertation aims to close these knowledge gaps in the wet Andean páramo, through data gathering from unique field experiments and statistical modeling for improving our understanding about fog occurrence and its implications on vegetation in this ecosystem. The generation of such knowledge will provide new insights related to the hydrological role of fog, which will allow to understand the effects of its presence in the Andean páramo water resources.

1.2 Objectives

This dissertation aims to investigate the specific role of fog on the hydrology of a wet páramo ecosystem, understanding the effects of fog occurrence on atmosphere-land interactions. This study therefore focused on the following specific objectives:

(1) To assess fog water estimates derived from three different types of fog gauges, and from them to understand its temporal dynamics and the importance of fog to annual rainfall.

(2) To quantify the contribution of fog water deposition to soil moisture, and to assess the relationship between meteorological variables and soil water content due to fog.

(3) To analyze the impact of fog on evapotranspiration rates, under different weather conditions (clear, foggy and rainy); and to evaluate how both fog and meteorological variables correlate with evapotranspiration variations.

1.3 Outline of the doctoral thesis

This dissertation consists of five chapters that address the topics about the influence of fog water on the ecohydrological processes in the Andean páramo. The outline of the chapters is depicted in Figure 1.1. Three manuscripts are the core of this thesis; two of them are published (Chapter 2 and Chapter 3) and the third is currently submitted to peer-review (Chapter 4).

Chapter 1 provides a general introduction and the importance of the study within the páramo ecosystem by reviewing past studies and identifying the knowledge gaps. This chapter also presents the objectives to address the research questions in the doctoral project and describes general aspects of the study area.

Chapter 2 is focused on the quantification of the atmospheric fog water through the process of cloud droplets deposition on fog collector meshes. For this approach, different types of passive fog gauges are assessed in order to obtain accurate estimations of fog water. Characteristics and the performance of each fog gauge are described and discussed; then from these data it is possible to determine the most suitable type of fog gauge for the páramo conditions. In addition, the analysis of fog dynamics is presented in this chapter.

Chapter 3 deals with the contribution of fog water to soil water content, analyzing whether the process of fog deposition on the tussock grasses leaves, reaches the soil and infiltration occurs, or if deposited water evaporates before reaching the soil. In addition, two different weather conditions are analyzed separately: fog with no precipitation conditions, and fog combined with other type of precipitation (e.g. drizzle , light rain, rain), to determine the importance of these inputs on soil water replenishment.

Chapter 4 is focused on understanding the impact of fog on evapotranspiration rates, comparing these rates under different weather conditions: clear conditions (no fog and no precipitation), foggy conditions (only fog presence) and mixed conditions (fog + rainfall). In addition, meteorological variables altogether with fog presence are analyzed to determine the main controls on evapotranspiration.

Finally, Chapter 5 presents the general synthesis and conclusions of this doctoral project, as well as the outlook for future research.

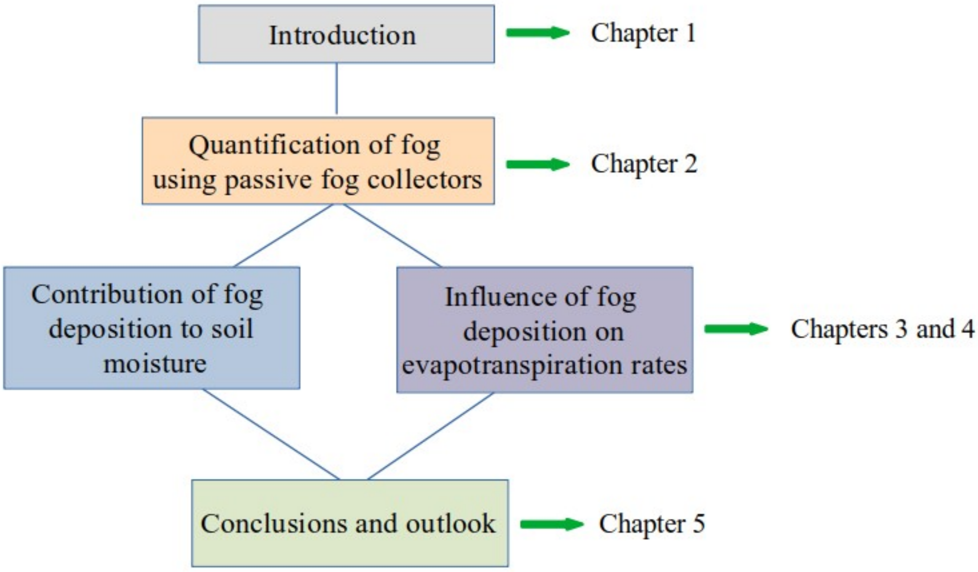

Figure 1.1: Outline of the doctoral thesis

1.4 Study area

This study was carried out at the Zhurucay Ecohydrological Observatory at 3°04'S and 79°14'W at an altitude ranging between 3,500 and 3,900 m a.s.l. (Figure 1.2). The observatory is densely-instrumented with hydrological, meteorological and ecohydrological sensors (Figure 1.3). It is located within a wet páramo ecosystem on the western side of the Andean cordillera in Southern Ecuador, at the headwaters of the Jubones River basin, which discharges towards the Pacific Ocean.

It has a drainage area of 7.53 km^2. Climate is mainly influenced by the continental air masses from the Amazon forest (Esquivel-Hernández et al., 2019). Mean annual precipitation is 1,210 mm ±100 mm $year^{-1}$ and 50% of the annual rainfall occurs at intensities of 2 mm h^{-1} or less, generally in the form of drizzle (Padrón et al., 2015). Intra-annual precipitation is highly uniformly distributed throughout the year, with minor seasonal differences. Fog is very frequent in the Andean páramo and primarily occurs combined with drizzle and light rain, with an average daily rate of 1.37 mm day^{-1} (Berrones et al., 2021). Fog occurs 68% of the time; despite it can be present at any time of the day, it is most common in the early morning and at night (Berrones et al., 2021). The mean annual temperature is 6.1 °C, mean relative humidity is 93.6%, and mean daily total solar radiation is 14

MJ m^{-2}. The wind blows predominantly from the east or northeast and wind speeds vary seasonally, with a monthly mean of 3.21 m s^{-1} from October to April and 4.77 m s^{-1} from May to September (Carrillo-Rojas et al., 2019; Padrón et al., 2015). The mean daily actual evapotranspiration is 1.7 mm day^{-1}, with a cumulative annual value of 622 mm (Ochoa-Sánchez et al., 2019).

The geology consists of compacted volcanic and volcanoclastic rock deposits formed during the glacial activity of the last ice age (Coltorti & Ollier, 2000; Hungerbühler et al., 2002) and mainly belongs to the Quimsacocha and Turi formations. For detailed geological information of the study area the reader is referred to Mosquera et al. (2015). The main soil types in the area correspond to volcanic origin Andosols (76%), with a minority of Histosols (24%) (WRB, 2015). These non-allophanic, humic and acidic soils result from the organic matter and the volcanic ash accumulation (Crespo et al., 2011). Andosols are black loamy soils with a high organic matter content (57.4%), low bulk density (< 0.9 g cm^3) and high water retention capacity (0.72 – 0.80 cm^3 cm^{-3} at saturation) (Mosquera et al., 2021b). Histosols have very high organic matter (21–66%), low bulk density (0.1–0.3 g cm^{-3}), and high water retention between saturation and field capacity (Crespo et al., 2011).

The dominant vegetation is represented by tussock grasses (> 80%) (genera *Calamagrostis* and *Festuca*), commonly known as “pajonal”, which are perennial plants that grow in bunches and reach heights of over 30 cm.

A comparison between historical data of 10 year precipitation from Zhurucay and data corresponding to the study period 2017 – 2019, showed that the time period used in this study corresponds as a normal year (Figure 1.3).

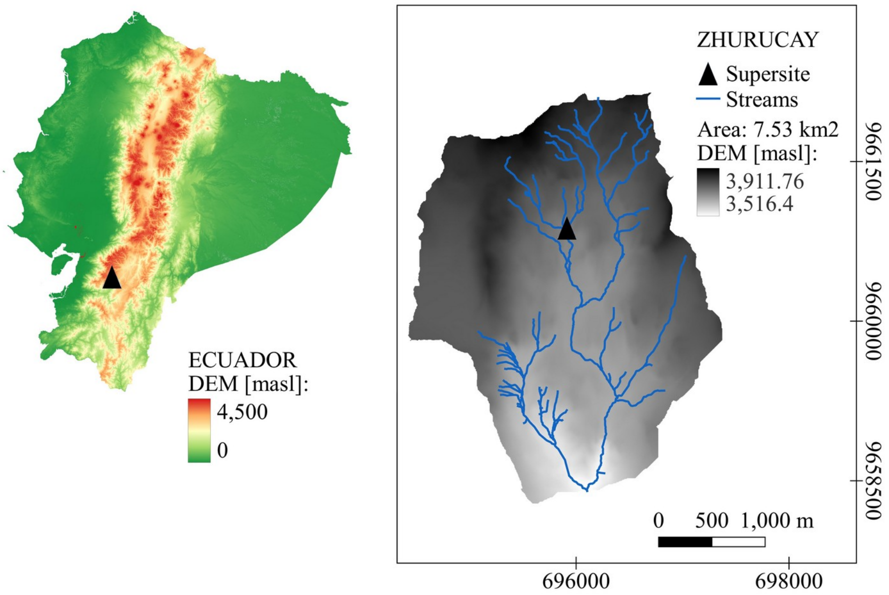

Figure 1.2: Zhurucay Ecohydrological Observatory

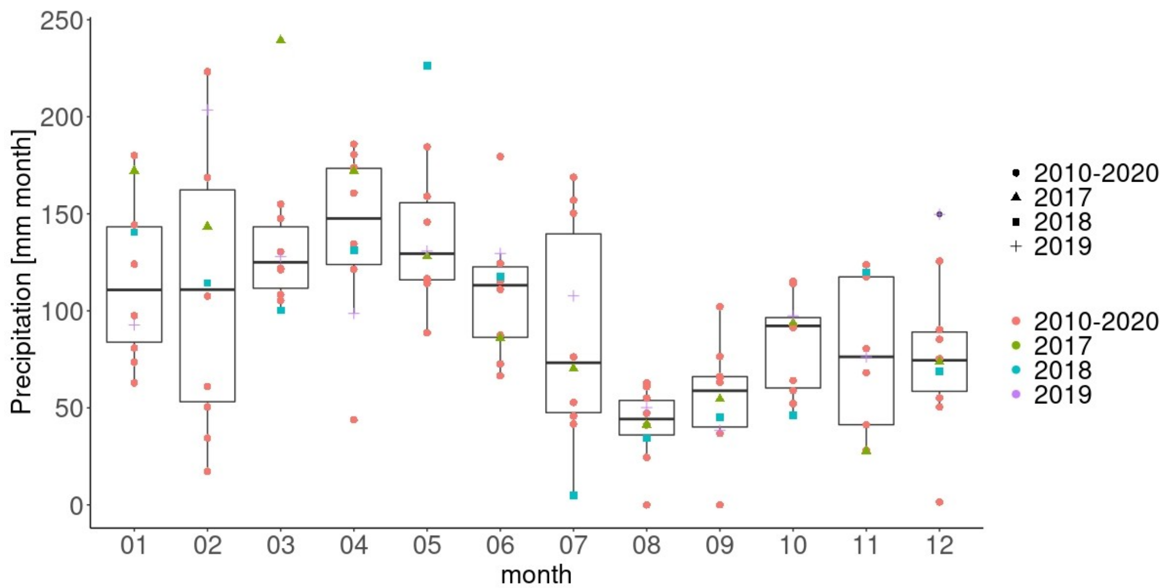

Figure 1.3: Comparison of ten year precipitation data and the corresponding study period (2017 - 2019) within the Zhurucay Observatory

Figure 1.4: a) Wet Andean páramo ecosystem with dominant tussock grasses vegetation in southern Ecuador; b) Instrumentation in the Zhurucay Ecohydrological Observatory

Chapter 2

2 Quantification of fog using passive fog collectors

In tropical highlands of the northern Andes, known as páramos, fog incidence is very frequent. Its quantification is not yet clear, mostly because of the complexity of distinguishing between fog and low-intensity rainfall. Moreover, there is uncertainty about the performance of the various types of gauges used to capture fog in this ecosystem. This study was carried out at the Zhurucay Ecohydrological Observatory (3,800 m a.s.l.), in southern Ecuador, assessing two cylindrical (Juvik and Wire Harp types) and two flat-screen fog collection gauges. A high-resolution laser disdrometer was installed next to the fog gauges, to measure precipitation of very low intensities and isolate fog from rainfall. We collected data over a 12-month period for four types of events—fog only, fog dominant, fog non-dominant and fog negligible. We evaluated the performance of the gauges during each type of event as well as to estimate the amount, rate and duration of fog. Fog was present during 68% of the days of the study, predominantly in the early morning and at night, and the average daily contribution was 1.37 mm. Most of the events occurred at rates below 0.3 mm h^{-1}. Measured rainfall was 1,200.1 mm, and fog estimations amounted to 340.1 mm. This fog contribution could bring total annual precipitation to about 1,540.2 mm, suggesting an extra 22% of water potentially available to the ecosystem—a very important asset for hydrological and ecological processes. This is the first study that has compared different types of fog gauges in the Andean páramo.

Related publication

Berrones, G., Crespo, P., Wilcox, B. P., Tobón, C., & Célleri, R. (2021). Assessment of fog gauges and their effectiveness in quantifying fog in the Andean páramo. *Ecohydrology*, *e2300*(April). https://doi.org/10.1002/eco.2300

2.1 Introduction

Evidence suggests that in many ecosystems, fog is among the most important sources of moisture (Bruijnzeel et al., 2005; Wang et al., 2019), and under particular environmental conditions, it provides extra moisture inputs that reduce water stress for various organisms (Wang et al., 2017). These ecosystems include the neotropical highlands of the northern Andes, known as páramos, where altitudes generally exceed 3,000 m a.s.l. In this ecosystem, the climate is humid and cold, and the vegetation is characterized by the presence of tussock grasslands and cushion plants.

Fog contains tiny, suspended water droplets having micron-size diameters (Regalado & Ritter, 2016) that can be easily trans ported by wind and atmospheric turbulence (Frumau et al., 2011a; Frumau et al., 2011b). Fog forms when the atmospheric water vapour concentration reaches saturation (Wang et al., 2017). Light rain or light drizzle commonly occurs along with fog, affecting its duration and thickness (Croft, 2003).

Existing studies recognize the critical role played by light rainfall and fog in the sustainability of fresh water in mountainous regions globally (Bruijnzeel et al., 2011; Klemm et al., 2012; Wilson & Barros, 2014). In the highlands, and in other ecosystems where the continuous presence of fog not only influences atmosphere–land interactions, such as water input, energy budget, transpiration and plant growth (Holwerda et al., 2010; Katata, 2014; Pryet et al., 2012; Ritter et al., 2008), but also can reduce evaporation. Moreover, fog affects vegetation–water interactions by reducing incoming solar radiation, decreasing atmospheric vapour pressure deficit and increasing leaf wetness frequency (Ramírez et al., 2018). In tropical alpine regions such as the Andean páramo, where natural grassland evapotranspiration is relatively low (Célleri & Feyen, 2009), the constant presence of fog—in addition to the high relative humidity—results in low transpiration rates (Buytaert et al., 2011a). In a review of potential impacts of climate change in tropical alpine regions, some researchers argue that water resources are the most important asset that will be negatively affected in the future (Buytaert et al., 2011a). Yet, the Andean páramo is among the least studied ecosystems. Although some studies have focused on the contribution of fog to water resources in tropical alpine regions, our knowledge of these dynamics in the páramo remains insufficient. Quantification of the contribution of fog is a primary need if we are to accurately estimate the water input to the ecosystem.

Most of the studies carried out in the Andes to assess fog water contribution have used passive fog collectors and have examined the spatial and temporal variability of fog-water collection, focusing on the potential use of fog as an alternative source of water (Cereceda & Schemenauer, 1993; Molina & Escobar, 2008). Some studies have analyzed the chemical composition and nutrient supply through fog water (Beiderwieden et al., 2005; Bendix et al., 2004). Fog plays a key role in the hydrology of tropical montane cloud forests, because its water input significantly enhances net precipitation (Eugster et al., 2006; Gomez-Peralta et al., 2008). For this reason, a number of studies have investigated (1) the effects of fog on the canopy water budget, through model simulations and observations during different stages of regeneration (Ramírez et al., 2018), the estimation of cloud water interception using the Rutter-type interception model (Domínguez et al., 2017); (2) the importance of forest structure in the capture of cloud water (Gomez-Peralta et al., 2008) and (3) the relationship between fog interception and meteorological variables (Bittencourt et al., 2019; Villegas et al., 2007). Such studies have shown that conditions like wind speed and direction, duration and frequency of fog events and the structural characteristics of the forests influence fog water interception (Bruijnzeel et al., 2005; Villegas et al., 2007). Nevertheless, in páramos, fog water interception by endemic vegetation has been measured and compared with fog inputs recorded by passive fog collectors (Tobón & Gil Morales, 2007). In addition, the occult precipitation (fog and drizzle) has been quantified to determine its temporal and spatial distribution (Cárdenas et al., 2017).

But although fog has been quantified, it is still unknown how well different measurement techniques work under páramo conditions. To our knowledge, no work has been done to compare the performances of different types of fog gauges under páramo conditions. Several different types of fog collectors have been developed, of both active and passive configurations, to measure fog occurrence and characterize local fog conditions (Frumau et al., 2011a; Frumau et al., 2011b; Holwerda et al., 2011; Juvik & Nullet, 1995; Schemenauer & Cereceda, 1994). Because of the diversity of applications for these devices and the variety of ways in which they operate, it is important to determine the efficiency of each individual type. Representative of the active category of fog collectors is the Caltech Active Strand Cloudwater Collector (CASCC), which is widely used in meteorological networks for the monitoring of traffic hazard conditions (Bruijnzeel et al., 2005) and the fog and cloud droplet spectrometer. Although these active fog collectors provide advantages on effectively separate the rain drops from the sampled fog water, they also present limitations such as the high power consumption, the uni-directional intake, which requires measures to ensure the intake is always facing the prevailing wind direction (Bruijnzeel et al., 2005); as well as the high cost. The passive category of fog collectors consists of flat panels and cylindrical designs; these have robust frameworks to which are attached mesh nets that are exposed to environmental conditions and main wind direction to collect fog droplets by a simple impact process (Frumau et al., 2011a; Frumau et al., 2011b; Holwerda et al., 2011; Schemenauer & Cereceda, 1991). In contrast to the fixed orientation of the flat panel collectors, the cylindrical collectors have uniform exposure to all wind directions, but their catching surface is smaller than that of the flat panel collectors. The louvred aluminium screen of the Juvik cylindrical device (Juvik & Ekern, 1978) has high collection efficiency and good drainage characteristics (Juvik & Nullet, 1995), while the cylindrical 'Wire Harp' collector (Goodman, 1985) maximizes the collection of water droplets on vertically strung wires (the collection efficiency being dependent on the number of filament arrays, strand diameter and filament inter-spacing) (Ritter et al., 2015). At the same time, the larger collection area of the flat panel design (Schemenauer & Cereceda, 1994) means that it might better measure fog when wind speeds and liquid water content are low (Holwerda et al., 2011; Schemenauer & Cereceda, 1995). Moreover, the flat panel preferentially should be used when wind direction is relatively constant.

Although several studies have been carried out to assess the performance of different fog gauges widely used in tropical montane cloud forests (Bruijnzeel et al., 2006; Frumau et al., 2011a; Frumau et al., 2011b; Holwerda et al., 2011), and under different climatic conditions (Bittencourt et al., 2019; Goodman, 1985; Gottlieb et al., 2019; Regalado & Ritter, 2017; Regalado & Ritter, 2019), none has been carried out in the páramo before now. Our study aims to close this knowledge gap in the wet Andean páramo by (a) comparing three types of fog gauges (cylindrical Juvik type, cylindrical Wire Harp and flat-screens) through analysis of the effects of wind speed, fog rate and duration of fog events; (b) quantifying the amount of fog water collected during fog events—both fog-only and fog associated with other types of precipitation and (c) characterizing the occurrences of fog and rainfall on a daily basis.

2.2 Materials and methods

2.2.1 Instrumentation

A variety of sensors within the Zhurucay Observatory were used for this study: (1) a laser disdrometer (Thies Clima Laser Precipitation Monitor [LPM] 5.4110.00.000 V2.4 × STD, with a resolution of 0.01 mm), which measures the size and falling velocity of drops and is well suited for the detection of different types of precipitation (e.g., drizzle, rain and mixed precipitation). The LPM generates a matrix with information providing the number of drops detected at 22 different drop sizes (from 0.125 to 8 mm) and at 20 different velocities (from 0 to 10 m s^{-1}); (2) a rain gauge (RG) (Texas Electronics tipping-bucket TE525MM, with a resolution of 0.1 mm) and (3) a meteorological station that records meteorological variables such as solar radiation, long and short wave net radiation, wind velocity and direction, atmospheric pressure, air temperature and Relative Humidity with the instruments Campbell Scientific CS300 Apogee pyranometer, CNR2—Kipp and Zonen Met-One 034B Windset anemometer. This instrumentation was complemented with three types of fog gauges to quantify fog water inputs (see section 2.2.2). All data were recorded at 5-min intervals, and the monitoring period for this study lasted 1 year (September 2017 to August 2018).

2.2.2 Fog Gauges

2.2.2.1 Installation and monitoring

As mentioned above, the fog gauges were installed at the Observatory, where the physical and climatic characteristics are the most suitable for these experiments. We considered three different designs of fog gauges in order to assemble the most appropriate structures for our field location. First, we made some modifications to all the gauges, such as the addition of protective covers on top, to avoid catching vertical precipitation and a system for automatic registration of collected water. On the basis of these modifications, we installed three types of fog gauges at the site: a cylindrical modified Juvik (JUV), a cylindrical wire harp (WH) and two flat-screen (FS) collectors. These gauges were placed 2 m above the ground surface.

The JUV gauge is a cylindrical structure that measures 40.5 cm high, 14 cm in outer diameter and 567 cm^2 in cross-sectional area; its collection surface is a louvered aluminum shade screen (Juvik & Ekern, 1978). The WH gauge measures 40 cm high, 14 cm in outer diameter and 560 cm^2 in cross-sectional area; its collection surface consists of 0.5-mm nylon fishing line running vertically and spaced 2 mm apart. Both these cylindrical gauges are equipped with 50-cm-diameter protective covers on top as well as two plastic funnels, one underneath the screen and the other one underneath the tipping-bucket rain gauge, which in turn was connected to a bucket/vessel via a plastic pipe/tube to drain the collected water. The FS fog gauge is constructed following Schemenauer & Cereceda (1994) and consists of a 1 m × 1 m metal frame covered with a polyethylene mesh that is woven in a rectangular pattern (1 mm × 3 mm) and stretched over the frame, but the mesh used in our study is different from the one used in Schemenauer & Cereceda (1994). This gauge too is equipped with a protective cover (101 cm × 126 cm) as well as with a metal collection gutter below the frame for draining the fog water. The plastic funnel was placed only underneath the tipping-bucket rain gauge which was connected to a vessel via a plastic tube (Figure 2.1).

Each of the gauges was connected to a tipping-bucket RG. To test the effectiveness of the fog gauges for water collection and measurement of the volume captured, a plastic funnel was placed beneath each gauge and connected to a collector vessel. The complete assembly, which consisted of two FS gauges, one JUV gauge and one WH gauge, was set up in close proximity to the other instrumentation. We used historical wind data from the Observatory to orient the two FS gauges, each facing one of the two predominant wind directions (i.e., one at 344° and the other at 284° to the north). After installation of the fog gauges, we tested their correct operation twice a week for 1 month before starting the data gathering for this study. Then, over the next 12 months (2017–2018), on a weekly basis, we downloaded data and performed maintenance on the instruments. In addition, although fog was measured automatically, we carried out several 2- to 3-day field campaigns to make observations of fog characteristics during both daytime and nighttime—including lengths of fog events; lag time between appearance of fog and (a) its accumulation on the collectors and (b) its dripping to the RGs and visibility during fog events (the LPM visibility measurements were not taken into account when discriminating between fog events because the values under foggy, cloudy or non-foggy conditions were very similar). Since this is the first time fog is measured in our study site, we worked on maintain data quality, and every weekly visit to the observatory, we checked the fog gauges' performance. In order to avoid the vertical precipitation in the vessels, they were covered with plastic, and every time data were downloaded, the water collected in the vessel was measured as well.

Figure 2.1: Design of the three types of fog gauges in the Ecohydrological Zhurucay observatory. All of the gauges have a cover on top to avoid vertical precipitation, and every gauge is connected to a Texas tipping-bucket rain gauge. (a) The cylindrical Juvik type, (b, c) flat screen panels facing the two main wind directions, and (d) the cylindrical wire harp type

2.2.2.2 Data correction

We performed a static calibration for every tipping-bucket RG in situ, to obtain the resolution of collection per tip where volume (e.g., in millilitres) is then converted to depth of fog deposition. Any fog deposition value is operationally defined and does not necessarily reflect the fog capturing characteristic of vegetation. A fog collector could let some fog droplets pass through uncaptured. A plant, however, with multiple layers of leaves that the fog has to pass through, is potentially able to capture more moisture from a given volume of foggy air that passes through. Moreover, we performed a comparison of the water collected from the fog gauges screens and then compared with water collected in the vessels, and losses were negligible. To accurately estimate the effective capture area of a fog gauge, both wind direction and wind speed must be taken into account. Because cylindrical gauges will be exposed equally to all wind directions, the collection surface will always correspond to only 50% of the total area of the cylinder, i.e., half of the surface facing the wind. Moreover, during our periodic field campaigns, we observed that during all fog events fog water condensed only on half of the cylinder surface regardless of the wind direction. Thus, the effective capture area was defined as the projected area (diameter of the cylinder times height). The flat- screen gauges were each mounted in a fixed orientation, facing in one of the two prevailing wind directions; consequently, our estimates of the effective capture areas were corrected by calculating the real angle of wind incidence for each gauge at 5-min intervals (as the difference between the wind direction recorded by the anemometer and the direction toward which the frame was facing), as shown in Equation 1.

$$V_c = \frac{V_{5\,min}}{max\left(\left|\sin\left(\overrightarrow{W_{5\,min}} + \alpha\right)\right|, \sin(\mu)\right)} \qquad (1.1)$$

where V_C = volume collected by the flat screen after correction; V_{5min} = volume collected by the flat screen every 5 min; w_{5min} = wind direction recorded by the anemometer at 5-min intervals; α = fixed angle between the flat screen and the north and μ = threshold fixed to a 10° angle when the angle of incidence is too small, in order to avoid overestimation.

To allow for the use of both flat-screen gauges simultaneously, additional corrections needed to be developed to compensate for the following drawback: because of their orientations toward different prevailing wind directions, the two flat screens captured water from different angles of orientation. Therefore, for every 5-min-interval reading, the result from the flat screen that had the better exposure to its wind direction was selected as the value for the correction calculation (via Equation 1.1). All of the above corrections were taken into account in determining the effective capture area for the flat-screen gauges. The estimated volume collected by the two flat screens used simultaneously (with the above-mentioned corrections applied) showed a close correlation with the estimated volume collected by the cylindrical fog gauges. The Pearson's correlation coefficients for the JUV and WH gauges with correction applied were 0.80 and 0.79, respectively.

2.2.3 Comparison of the three types of fog gauge

To compare the fog gauges' performance, we used data from fog-only events and from events during which other types of precipitation occurred along with fog. For each event, we determined (1) the rain- drop size distribution, (2) the relationship between the depth of fog deposition and the rate and (3) the relationship between the duration and the rate. Finally, we analyzed the effect of wind speed on the fog water collection.

2.2.3.1 Classification of fog events

Data were analyzed per event, on the basis of the measurements made during field campaigns. At our study site, we monitored the time of fog occurrence and its contact with the device surface. We considered as independent events those lasting longer than 10 min and separated from other events by at least 30 min. Fog or cloud water droplets are very light in weight and therefore stay suspended in the air. Unlike rain or drizzle, fog does not reach the soil unless there is an obstacle that captures the water droplets from the air. The obstacle is the collector screen in the case of this study; however, there is no collector screen in the natural environment. Fog gauge measurements can be represented as “cloud water flux” which is the horizontal flux of water, instead of a vertical flux like rainfall (Giambelluca et al., 2011a). Therefore, from now on, when we mention fog, we refer to cloud water flux.

Information from the fog gauges as well as from the LPM and the RG was used to classify the different types of events. For this study, we defined four types of events: “fog only” (FO), “fog dominant” (FD), “fog non-dominant” (FND) and “fog negligible” (FN), depending on the proportion of fog characterizing the event. (It is particularly important to mention that during field campaigns, we observed that whenever fog was present without another type of precipitation [e.g., drizzle or rain], data were recorded only by the fog gauges and not by the LPM or the RG.) The criteria for the event classification were as follows: (i) FO events: some amount of fog was captured by the fog gauges but none by the LPM or the RG, and the fog proportion of the total event depth was 100%; (ii) FD events: the water collected by the fog gauges was greater than the amount recorded by the LPM and the RG, and the fog proportion of the total event depth was between 50% and 99%; (iii) FND events: the amounts captured by the LPM and the RG were greater than the amount captured by the fog gauges, and the fog proportion of the total event depth was between 10% and 50%; (iv) FN events: the fog proportion of the total event depth was between 0% and

10%. Moreover, to reduce the bias due to wind-driven precipitation in the events, we considered only the events with wind speeds in a range of $0 \leq u \leq 4 m\ s^{-1}$. Similar criteria were defined by Cárdenas et al. (2017) and by Frumau et al. (2010).

2.2.3.2 Raindrop size distribution during events and its effect on depth of cloud water deposition

To determine the type of precipitation (drizzle, light rain, rain or heavy rain) that was combined with fog during an event, we first noted the number concentration, or number of raindrops per unit volume per unit size—N(D)—from the LPM data telegram. In Equation 1.2, *N(Di)* is the number concentration in *ith* size class ($mm^{-3}\ mm^{-1}$), *Di* is the mid- size diameter of the *ith* class (mm), *A* is the cross sectional area of the sensor (m^2), *t* is the measuring time (seconds), *nij* is the number of drops within the *ith* size and *jth* velocity class and *Vj* is the fall speed of the *jth* velocity class ($m\ s^{-1}$).

$$N(Di)=\sum_{j=1}^{20} \frac{nij}{AtVj\,\Delta Di} \qquad (1.2)$$

Then, we calculated the mean volume diameter *Dm* (mm) at 5-min intervals. In Equation 1.3, *N(D)* is the drop size distribution, *D* is the particle diameter and D^3 and D^4 are the third and fourth moments calculated for each spectrum.

$$Dm=\frac{\int_0^\infty N(D)\,D^4\,dD}{\int_0^\infty N(D)\,D^3\,dD} \qquad (1.3)$$

The categorization based on the *Dm* was prepared according to the procedure used by Orellana-Alvear et al. (2017), where $0.1 < Dm\ [mm] \leq 0.5$ corresponds to drizzle, $0.5 < Dm\ [mm] \leq 1.0$ corresponds to light rain, $1.0 < Dm\ [mm] \leq 2.0$ corresponds to rain and $Dm\ [mm] > 2.0$ is defined as heavy rain. In addition, we calculated the volume, the percentage and the raindrop size distribution of all types of precipitation during each event. Finally, we noted the differences in water collection among the three types of fog gauges for each type of event.

2.2.3.3 Relationship between depth and duration vs. cloud water flux rate of events

To evaluate the differences among the fog gauges, we used boxplots to compare the depth of cloud water deposition collected by the three gauge types during the four types of events (FO, FD, FND and FN) at various rates (0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8 and >0.8 mm h^{-1}). In addition, we calculated the number of events of each type of fog event at these same rates. To determine the relationship between the duration (hours) and the rate (mm h^{-1}) of each type of fog event (FO, FD, FND and FN), we constructed a scatter plot for each fog gauge. These plots display the variations among the gauges and also elucidate whether a longer event duration implies a greater cloud water rate.

2.2.3.4 Effect of wind speed on the depth of cloud water

We selected different wind speed ranges (0–1, 1–2, 2–3 and 3–4m s^{-1}) to assess whether wind speed affects the amount of fog water collected for each type of event (FO, FD, FND and FN). Using these data, we generated boxplots for each gauge. In addition, to compare the volumes collected by the different fog gauges on an event basis, we used the Pearson's correlation coefficient and least squares linear models.

2.2.4 The diurnal cycle of fog and rainfall

To analyze how fog and rainfall are distributed during the day, data were aggregated on an hourly basis. For every hour of the day, we calculated the total volume of each type of precipitation (fog, drizzle, light rain, rain and heavy rain). In addition, we calculated the total duration (number of hours per day) of each type of event (FO, FD, FND and FN).

2.3 Results

2.3.1 Comparison of the three types of fog gauge

2.3.1.1 Selection of events for analysis

Table 2.1 provides a summary of the number, duration and total amounts of cloud water from the events captured by the fog gauges (JUV, WH and FS), the LPM and the RG for each of the four types of fog events. A total of 609 events were selected, having a combined total duration of 1,635 hours. For the FO events, the mean duration was 84 min, and the median duration was 70 min. The JUV gauge captured a mean of 0.18 mm, the WH gauge captured 0.21 mm and the FS gauge captured 0.23 mm. For the FD events, the mean and the median durations were 307 and 215 min, respectively. The JUV gauge collected a mean of 1.9 mm, and the WH and FS gauges 1.6 mm each. For the FND events, the mean and median durations were 298 and 175 min, respectively. The mean by the JUV, WH and FS gauges were 1.5, 1.4 and 1.1 mm, respectively. Finally, for the FN events, the mean and median durations were 88 and 40 min, respectively. The JUV gauge collected a mean of 0.03 mm, the WH gauge 0.07 mm and the FS gauge 0.1 mm. On average, the fog gauges collected 340.1 mm of cloud water flux, the LPM registered 1,200.1 mm of rainfall and the RG recorded 1,113.5 mm of rainfall. Considering the rainfall and the cloud water flux, the precipitation could be potentially 1,540.2 mm.

Table 2.1 Number, total duration, and water depth per unit vertical cross- sectional area of the gauge of each of the four types of fog events as recorded by the three fog gauges, the LPM, and the RG during the 12-month study period

Type of event	Number of events	Percent of total	Total duration (hours)	Total cloud water flux (mm)			Total rainfall (mm)	
				JUV	WH	FS	LPM	RG
Fog only (FO)	51	8.4	71	9.3	10.6	11.7	0	0
Fog dominant (FD)	57	9.4	291	113.6	92.3	92.6	46.1	39.4
Fog non-dominant (FND)	154	25.3	765	233.2	219.4	165.8	578.6	529.8
Fog negligible (FN)	347	56.9	508	11.6	25.6	34.5	374.4	356.1

2.3.1.2 Raindrop size distribution during events and its effect on depth of cloud water deposition

The rainfall categorization based on the mean volume diameter *Dm* (mm), calculated with the LPM, enabled us to obtain the raindrop size distribution of the different types of precipitation (drizzle, light rain, rain and heavy rain) for each type of fog event (FO, FD, FND and FN). The three types of fog gauges exhibited differences in fog collection and precipitation particles change depending on fog type. In the following results, we describe the percentage of drizzle, light rain, rain or heavy rain contained in the FD, FND and FN events through the data from the LPM, which was described in Section 2.2.3.2. The percentage of fog is entirely from the three fog gauges.

As shown in Figure 2.2, the fog event type having the highest cumulative volume was the FND. During the FD events, all three gauges (along with the LPM) registered very similar distributions of precipitation particle sizes as a percent of total volume: for the JUV, 71.2% as fog, 20.3% as drizzle, 7.9% as light rain and only 0.6% as rain; for the WH, 66.7% as fog, 23.4% as drizzle, 9.1% as light rain and 0.8% as rain and for the FS, 66.8% as fog, 23.4% as drizzle, 9.0% as light rain and 0.8% as rain. For the FND events, the JUV and the WH gauges with the LPM registered roughly similar distributions: 29.2% and 28.0% fog, 17.5% and 17.8% drizzle, 51.0% and 51.9% light rain, 2.3% rain and only 0.02% heavy rain, respectively, whereas the FS gauge with the LPM showed 22.7% fog, 19.1% drizzle, 55.7% light rain, 2.5% rain and only 0.02% heavy rain. Finally, for the FN events, there were noticeable differences among the gauges, especially for the fog proportion: the JUV gauge showed 3.0% fog, the WH gauge 6.4% and the FS gauge 8.5%. For the other precipitation types, the JUV, WH and FS gauges with the LPM showed the drizzle proportion as 15.3%, 14.7% and 14.4%, respectively; light rain as 66.7%, 64.4% and 63.0%, respectively, and rain and heavy rain as nearly identical (differences of <1% and < 0.1%, respectively, among the three gauges).

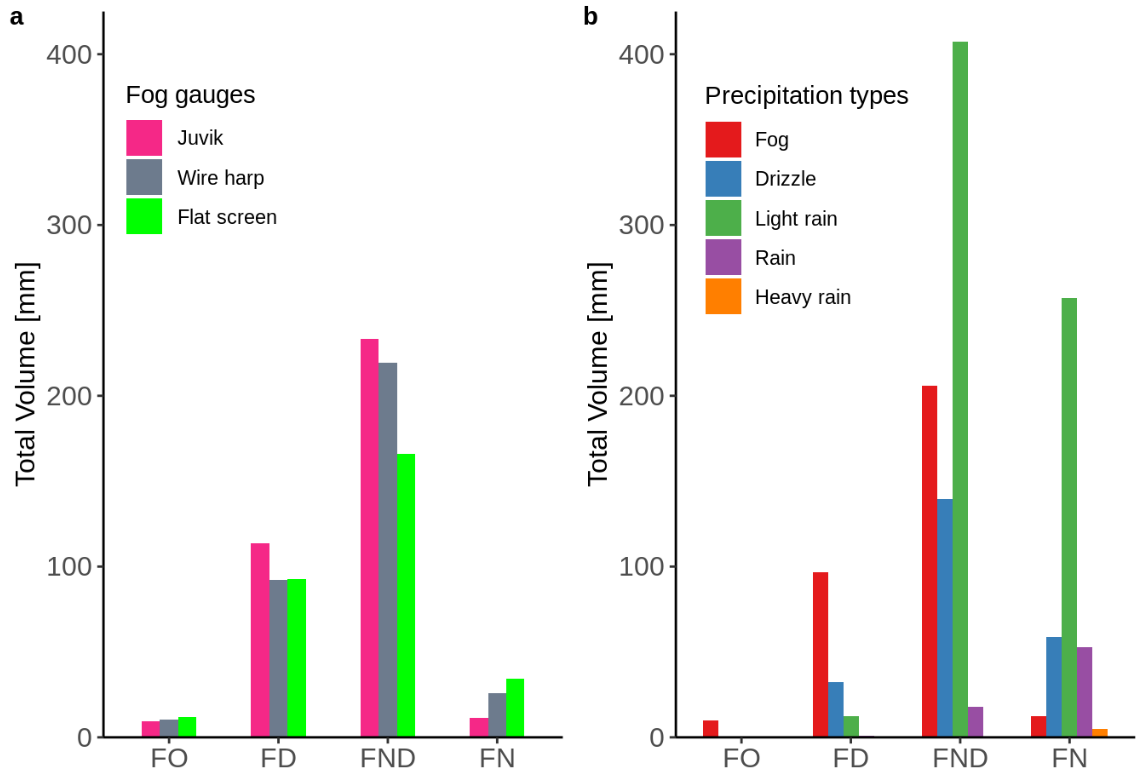

Figure 2.2 Distribution of precipitation during each of the four types of fog events, as recorded by the three fog gauges along with the LPM disdrometer: (a) annual total amounts collected during the different fog events and (b) distribution of each type of precipitation during the different fog events. Fog represents the median collected by the three gauges; the drizzle, light rain, rain, and heavy rain volumes were calculated from the mean volume diameter (Dm) via the LPM disdrometer

Figure 2.3 shows that for the FO events, the JUV, WH and FS gauges all registered similar amounts; most event volumes ranged from 0.05 to 0.28 mm, but some were as low as 0.01 mm and some as high as 1.8 mm. For the FD events, the fog gauges registered slightly different amounts—most between 0.3 and 3.3 mm. The drizzle component varied between 0.01 and 1.4 mm, light rain and rain were almost insignificant and heavy rain was nonexistent. In contrast, for the FND events, the light rain component was predominant, followed by fog and then drizzle; particles of rain and heavy rain are present as well but did not contribute much (18.1 mm in total). Only a few of the FND events had amounts > 20 mm. For the FN events, the light rain and rain components are predominant, but there are greater outliers for these events than for the other types. Only two FN events had total amounts > 15 mm.

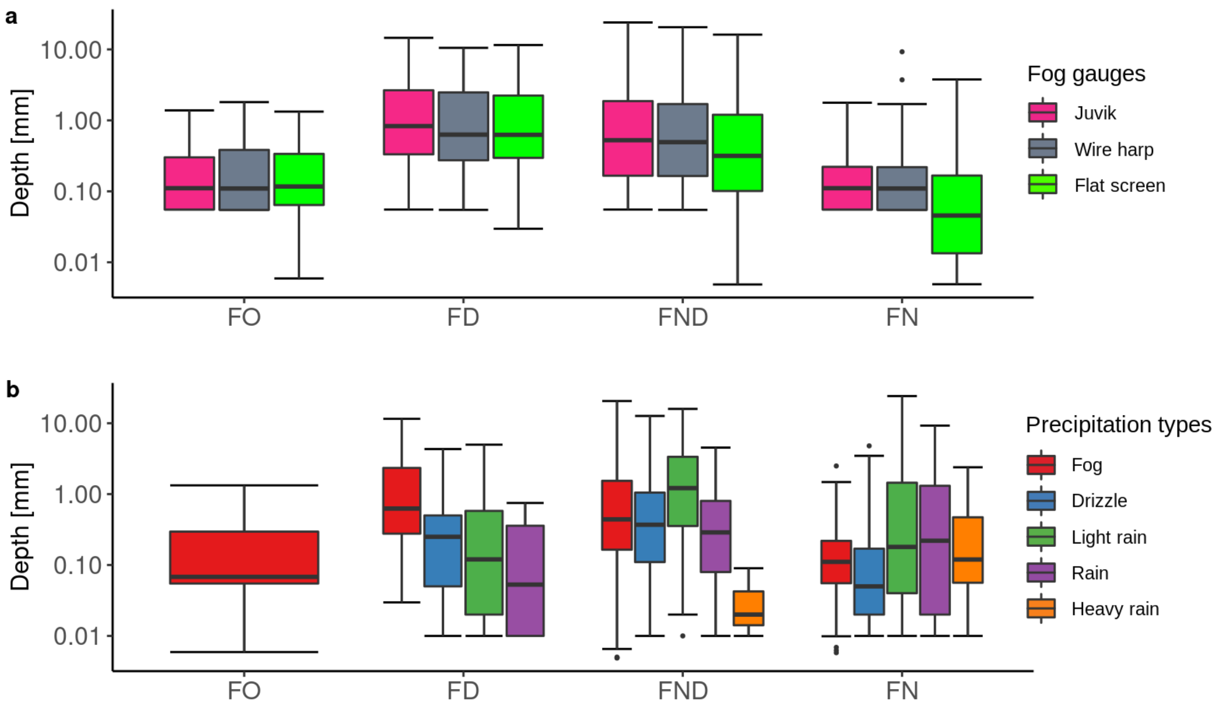

Figure 2.3 Boxplot comparison of the precipitation per event collected by the three fog gauges during the FO, FD, FND, and FN events: (a) cloud water collected by each gauge type and (b) distribution of each type of precipitation during the different fog events. Fog represents the median collected by the three gauges; the drizzle, light rain, rain, and heavy rain volumes were calculated from the mean volume diameter (Dm) via the LPM disdrometer. Y axis scale was converted to log 10

2.3.1.3 Relationship between depth and duration vs cloud water flux rate of events

From data in Figure 2.4, we can infer that over 85% of the events (FO, FD, FND and FN) occurred at rates between 0 and 0.6 mm h^{-1}. The FO events that occurred within this range were recorded by all three gauges; however, only the FS gauge could record FO events at higher rates (> 0.6 mm h^{-1}). At rates in the 0–0.4 mm h^{-1} range, the fog amounts collected by the JUV, WH and FS gauges varied between 0.06 and 0.61 mm, 0.05 and 0.60 mm and 0.06 and 0.60 mm, respectively. For the FD and the FND events, the fog gauges showed a high variability when registering events having rates between 0.6 and > 0.8 mm h^{-1}.At the higher rate > 0.8 mm h^{-1}, the JUV recorded four events, whereas the WH and FS gauges recorded only two, respectively. For the FN events, all (100%) occurred at intensities ranging from 0 to 0.6 mm h^{-1}. It should be noted that for the events in the

0.2–0.6 mm h^{-1} range, the FS gauge collected higher volumes (3.8 mm) than did the JUV (0.9 mm) and the WH (1.7 mm) gauges.

From Figure 2.5, we can see that of the four fog event types, the FO events had the shortest duration, with a mean of 1.4 hours (78% lasted less than 2 hours, and only 4% lasted more than 3 hours). With respect to intensity, over 95% of the FO events were below 0.5 mm h^{-1}. In other words, almost all of the FO events had short durations and lower intensities. For the FD events, the maximum duration was 20 h, and the mean duration was about 5.1 hours (61% lasted less than 5 hours and < 40% more than 5 hours). With respect to intensity, most of the FD events fell into the 0–0.5 mm h^{-1} range (there were minor differences among the gauge readings—the JUV recording 84.2%, the WH 87.7% and the FS 89.5%). The longer-duration events (10–20 hours) reached intensities greater than 0.5 mm h^{-1} but less than 1 mm h^{-1}. For the FND events, the mean duration was 5 hours, and the maximum 35 hours (68.8% of these events lasted less than 5 hours, while 27.9% lasted between 5 and 20 hours). As with the FD events, the intensities of the longer-duration FND events did not exceed 1 mm h^{-1}, according to all the fog gauges. Finally, for the FN events, the mean and maximum durations were 1.5 and 32 hours, respectively, and the great majority (94.2%) of these events had intensities in the range of 0–0.5 mm h^{-1}.

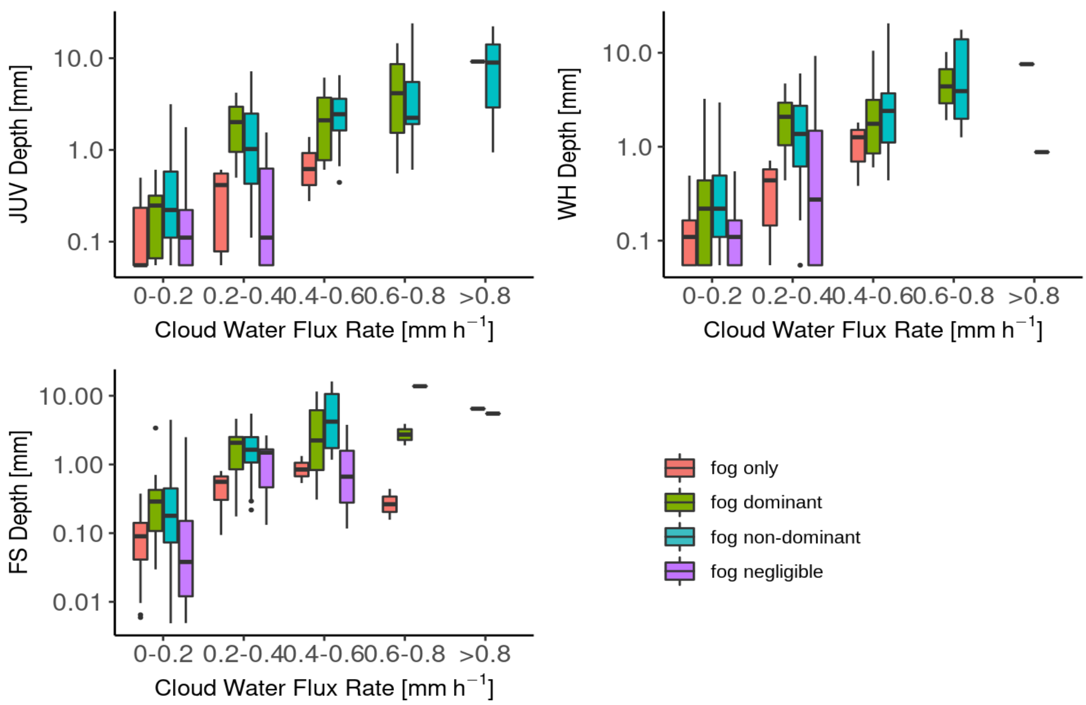

Figure 2.4 Cloud water collected by the different gauges for the four types of fog events, by rate of event (mm h^{-1}). Y axis scale was converted to log 10.

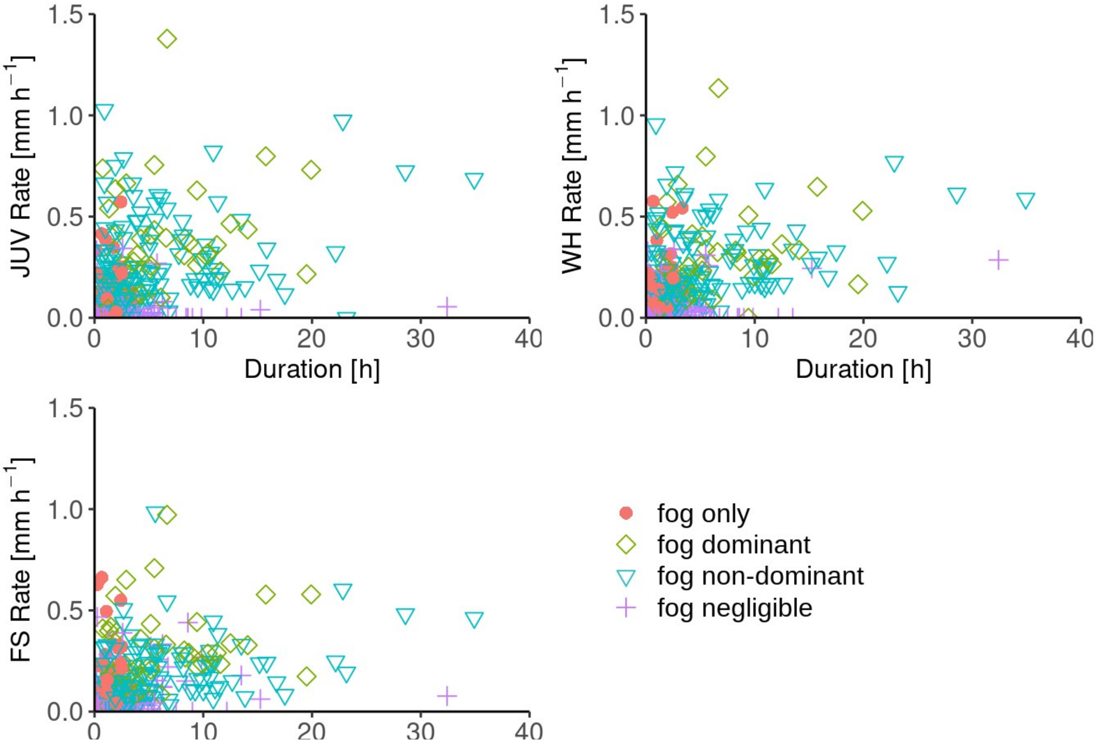

Figure 2.5 Correlation between duration and rate for the four types of fog event, as shown by the different types of fog gauges

2.3.1.4 Effect of wind speed on the depth of cloud water

From data in Figure 2.6, it is apparent that the higher-amount fog events were associated with higher wind speeds. In addition, at speeds between 3 and 4 m s^{-1}, the FO and FD events were the most frequent (41.2% and 47.4%, respectively), whereas when wind speeds were between 2 and 3 m s^{-1}, 50.7% of the events were FND and 36% were FN events. For the FO events, at higher velocities (3–4m s^{-1}), the variability was greater: the WH gauge showed an extreme event (1.8 mm), whereas the maximum values for the JUV gauge was 0.61 mm and for the FS gauge was 0.7 mm. For the FD events, when wind speeds were between 3 and 4 m s^{-1}, the amounts collected ranged from 0.4–14.6 mm for the JUV gauge to 0.4–10.5 mm for the WH gauge, and 0.3–11.5 mm for the FS gauge. At lower wind velocities, the maximum amount collected by the JUV gauge was less than 6 mm, and less than 5 mm for the WH and the FS gauges. For the FND events, there was greater variability among fog gauges when wind speeds were between 2 and 4 m s^{-1}, and the FS gauge collected lower amounts than did the JUV and the WH gauges. Finally, for the FN events, at wind speeds of 3–4m s^{-1}, the FS gauge collected the greatest amount of fog, with a maximum value of 3.8 mm; in comparison, the JUV gauge and the WH gauge collected maximum values of 0.5 and 0.2 mm, respectively. On the other hand, at lower wind velocities (1–2 m s^{-1}), the WH gauge collected greater amounts than the JUV and the FS gauges.

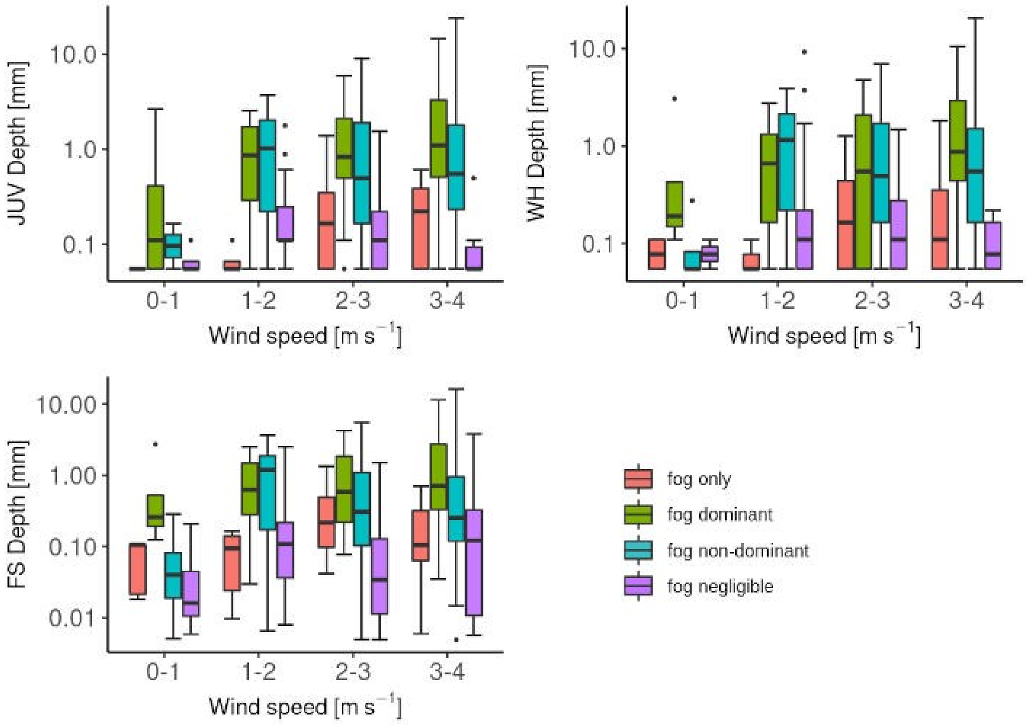

Figure 2.6: Boxplots showing the impact of wind speeds on cloud water collection in a range of 0 > u > 4 m s^{-1}. Y axis scale was converted to log 10.

The results of the linear regression model for all the pairs of fog gauges are set out in Figure 2.7. The three types of fog gauges showed a strong correlation: the coefficient of determination (R^2) between the JUV gauge and the WH gauge was 0.917; that between the JUV and FS gauges was 0.906 and that between the WH and FS gauges was 0.865. It can be seen that in the correlation between the JUV gauge and the WH gauge, the fog events occurring at lower wind velocities were more dispersed. In contrast, the correlation between the JUV and the FS gauges, as well as that between the WH and the FS gauges, showed that the dispersion in events was due to higher wind velocities. Overall, every fog gauge showed a higher correlation coefficient for 0–2m s^{-1} than 3–4m s^{-1}.

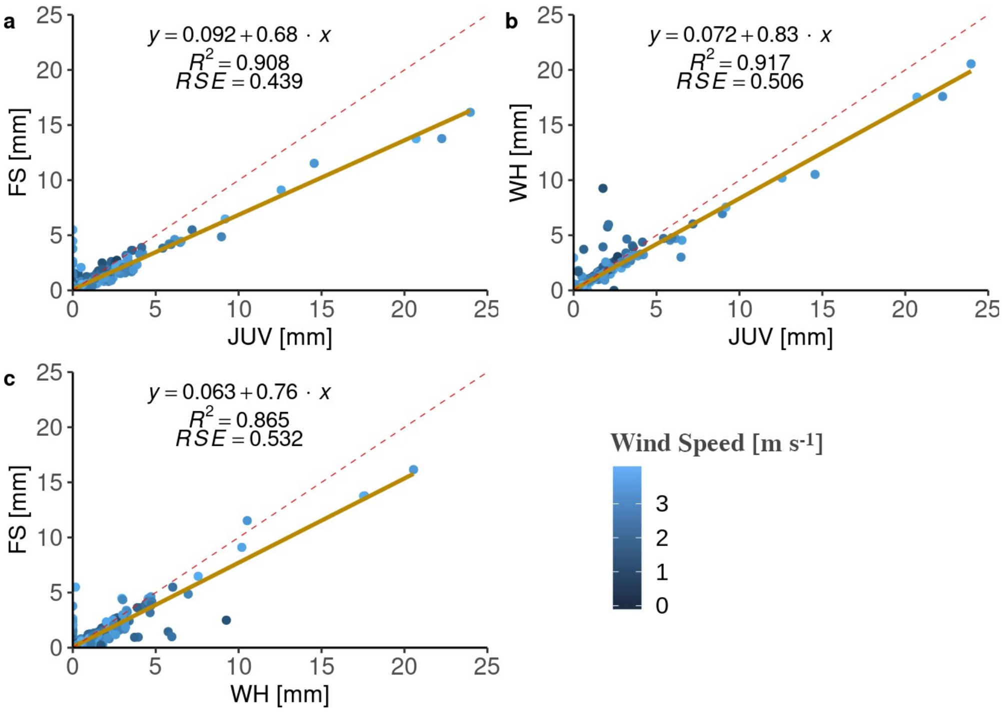

Figure 2.7: Linear model and correlational analysis for the three types of fog gauges as a function of wind speed during fog events: (a) relationship between the JUV and the FS gauges and the equation for the linear model; (b) correlation analysis for the JUV and the WH gauges; and (c) linear regression for the WH and the FS gauges

2.3.2 The diurnal cycle of fog and rainfall

In this páramo, most of the days are foggy whether or not there is rain. Figure 2.8 presents an overview of the mean daily cycle of fog and rainfall at the research site. During the 365 days of monitoring, fog occurred on 249. Typically, fog is most common in the early morning and during the night, and while still present at other times of the day, it is less frequent and less intense. Drizzle is very common as well, and our field observations showed that most of the time both fog and drizzle occurred, with fog tending to be more intense in the early morning, in the afternoon and at night. Light rain, sometimes present during the morning hours, generally starts to increase around midday and surpasses the fog and drizzle in volume until about 18 hours. Rain and heavy rain are not frequent nor strong; however, they could be present in combination with the other types of precipitation during a few hours in the afternoon. Table 2.2 shows the hours and percentage for each precipitation type in each event type. Considering as night-time (6 pm to 6 am), fog amounts corresponded to 14.5% to the daily precipitation, whereas in daylight (6 am to 6 pm), fog corresponded to 11.3%. On the other hand, drizzle amounts corresponded to 11.8% during night-time and 9.5% during daylight to the daily precipitation.

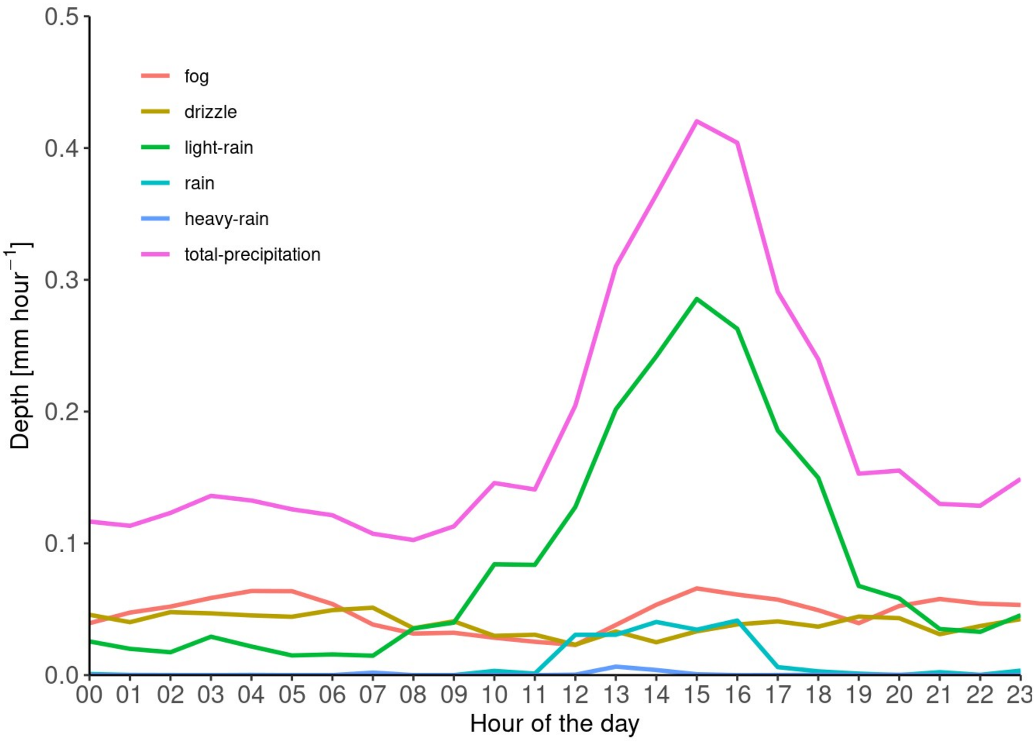

Figure 2.8: Hourly distribution of fog and other types of precipitation over the course of the study. Total precipitation represents all types of precipitation, including fog

Table 2.2. Time occurrence and percentage of fog and other types of precipitation for each event type

	Fog only		Fog dominant		Fog non-dominant		Fog negligible	
	Hours	**%**	**Hours**	**%**	**Hours**	**%**	**Hours**	**%**
Fog	71	100	12.3	4.2	37.5	4.9	32.4	6.4
Drizzle	-	-	261	89.7	496	64.8	275	54.1
Light rain	-	-	17	5.8	225	29.4	187	36.8
Rain	-	-	0.8	0.3	6	0.8	12	2.4
Heavy rain	-	-	-	-	0.5	< 0.1	1.6	0.3

2.4 Discussion

2.4.1 Contribution of cloud water in the Andean páramo

Between September 2017 and August 2018, precipitation in the Andean páramo amounted to 1200.1 mm, and on average, 340.1 mm (22%) was collected by the fog gauges (Table 2.1). This cloud water potentially could be an important contribution to the total precipitation at our study site. The contributions of fog to total precipitation found by other studies in various ecosystems are shown in Table 2.3 (to facilitate comparison, these values have been converted to annual amounts to match the monitoring period of our study). Studies with different methods (different fog gauges or using canopy water balance) were not considered in Table 2.3 for discussion. The values obtained by our study are far below those reported by Bendix et al. (2008) and Rollenbeck et al. (2011) in the Ecuadorian Andes and are also lower than the fog contribution to the water budget found by Bittencourt et al. (2019), working in Tropical Montane Forest. Increasing precipitation, especially the water input by horizontal rain and cloud/fog water deposition could be associated due to high cloudiness and high wind velocities (Bendix et al., 2008). Clouds persistently engulf many tropical mountains at elevations cool enough for them to form, creating isolated patches of habitat with markedly more fog and mist compared with lower elevations (Helmer et al., 2019). On the other hand, our results were higher than the values reported by Cárdenas et al. (2017) for two sites in the Colombian páramos, as well as those reported by Holwerda et al. (2010) and Gomez-Peralta et al. (2008) for Tropical Montane Cloud Forest. Results similar to ours were found by Cárdenas et al. (2017) for another Colombian páramo site (Chingaza) and by Tanaka et al. (2011) for an evergreen forest.

The páramo is characterized by low-intensity rainfall, the presence of low clouds and the occurrence of drizzle, such that only 12% of the days are completely dry (Padrón et al., 2015). Moreover, we observed during our field work that fog is persistent throughout the day and most of the time occurs simultaneously with other types of precipitation. Our quantification of fog events showed that drizzle and light rain were the precipitation types most frequently associated with FD, FND and FN events (Figures 2.2 and 2.3). Our finding that over 80% of the FO events occurred at rates lower than 0.2 mm h^{-1} (Figure 2.4) is consistent with results reported by Cárdenas et al. (2017) in Colombian páramo (0.12 mm h^{-1}) and with those of Regalado & Ritter (2017), who observed that most of the events at an altitude of 1,093 m a.s.l. occurred at rates of less than 0.2 mm h^{-1}. In addition, at our site, FO events were typically short term (< 3 hours) (Figure 2.5). Similar characteristics are described by Obregon et al. (2011) for a tropical lowland forest (4.6 hours on average) and Montecinos et al. (2018a) for the semiarid Coquimbo region in Chile (between 20 min and 11 hours 40 min). In contrast, the FO events reported by Holwerda et al. (2011) for a Puerto Rican elfin cloud forest were of considerably longer duration (16 hours on average). In the páramo, cloud water is more frequent at short time intervals; it forms from warm, moist air that rises by orographic uplift, in which prevailing winds force air against mountains and upwards, and convection, in which the land surface emits absorbed solar radiation, heating the impinging air as it rises (Helmer et al., 2019).

Table 2.3.Studies of fog contribution in different ecosystems

Reference	Ecosystem	Location	Altitude (m a.s.l)	Monitoring period (months)	Rainfall (mm)	Cloud water (mm)	Cloud water (%)
This study	Andean Páramo	Southern Ecuador	3,770	12	1,200.1	340.07	22.1 (potentially)
Cárdenas et al. (2017)	Andean Páramo	Colombia-Chingaza	3,570 – 3,730	12	3,398	214 – 228	6.3 – 6.7
	Andean Páramo	Colombia-Belmira	3,118	7	852	97	11.4
	Andean Páramo	Colombia-Romerales	3,840 – 4,040	7	384 – 587	92 - 128	20 – 27.8
Bendix et al. (2018) and Rollenbeck et al. (2011)	Tropical mountain rain forest – páramo transition zone	Southern Ecuador	3,200	12	4,000	2,500	~ 40
Bittencourt et al. (2019)	TMCF	Brazil	2,000	12	1,956	465	19.2
Gomez-Peralta et al. (2008)	TMCF	Yanachaga-Chemillén National Park, Central Peru	2,468 – 2,815	12	2,625	21	0.8
Holwerda et al. (2010)	TMCF	Veracruz, eastern Mexico	2,100	24	3,180	-	≤ 2
Tanaka et al. (2011)	Hill Evergreen Forest	Northern Thailand	1,685	35	5,513	1,033	~ 16

TMCF = Tropical Montane Cloud Forest

2.4.2 Comparison of fog gauges

In reviewing the literature, we found no data on the performance of fog gauges in the Andean páramo. Our study, carried out under páramo conditions (low temperature and atmospheric pressure, high solar radiation and high relative humidity) at an altitude of 3,770 m a.s.l., is the first to compare and contrast different types of fog gauges. The efficiency of these gauges in collecting fog water depends on both wind velocity and liquid water content (Regalado & Ritter, 2017).

In the case of the FO events, the FS gauge collected more total amounts than the JUV and WH gauges (Table 2.1), but the WH gauge showed more fluctuations in water collection than either the JUV or FS gauges. The difference is linked to the surface contact area of the FS gauge and suggests that this gauge is more efficient at capturing fog water when the liquid water content is low or winds are light (Bruijnzeel et al., 2005). This observation is in agreement with that of Holwerda et al. (2011), who found that at times of low fog incidence in an elfin cloud forest, the cylindrical JUV gauge showed a delayed response in collection in comparison with FS gauges. Further, Frumau et al. (2011a) mention that larger evaporative losses from the JUV gauge surface, as well as delayed drainage, result in lower collection efficiency for events with low liquid water content.

At low wind velocities (0–2 m s^{-1}), the differences between the three fog gauges were slight (Figure 2.6), but as wind velocities increased, greater differences were seen. Although there is a good linear relationship among the three gauge types with respect to wind velocity (Figure 2.7), the WH gauge seems to be the most affected by variations in velocity. The strings in this type of gauge make the intercepted droplets more susceptible to being blown off by high winds. Our study's finding of reduced collection by the WH gauge corroborates the earlier findings of Holwerda et al. (2011);Frumau et al. (2011a) and Frumau et al. (2011b) that the efficiency of the JUV gauge is independent of wind speed. However, Ritter et al. (2015) reported similar collection yields for the WH and JUV gauges.

As shown in Table 2.1, in the case of FD and FND events, the JUV gauge collected the highest total amount, with over 20 mm (or 22.9%). Through the mean volume diameter (Dm) categorization (Figure 2.2), we could define the other types of precipitation different than fog that every gauge collected. Our results showed that the JUV gauge collected 71.2% of fog and 20.3% of drizzle, whereas the WH and FS gauges collected lower percentages of fog but higher percentages of drizzle. A possible explanation for these differences might be that the aluminum louvered screen of the JUV gauge is more rigid, giving it stability and good drainage—attributes that favour the capture of fog water (Juvik & Nullet, 1995).

As shown by these data, the three types of fog gauges performed differently with respect to total fog water collection. Although these differences were not statistically significant under fog-only conditions, under conditions of fog combined with other types of precipitation, the FS gauge showed the lowest collection efficiency. Giambelluca et al. (2011b) mention that despite corrections for wind direction, the FS gauge depends on numerous site- and installation-specific variables. In addition, García-Santos & Bruijnzeel (2011), using an FS gauge with a fixed orientation, reported an underestimation of fog incidence due to variations in wind direction and wind speed. It was because of these limitations that for our study, we used two FS gauges simultaneously, with different orientations, to achieve additional corrections (Equation 1.1) that would render them comparable with the omnidirectional cylindrical fog gauges. Although differences in total amounts varied between 20 and 60 mm, the coefficient of determination between the FS and the JUV gauge was higher than that between the FS and the WH gauge (Figure 2.7). It should be noted that because of differences in construction of our apparatus (we mounted two FS gauges in two different fixed directions to more accurately capture fog), our results could vary from those obtained by the standard fog collector.

Cylindrical fog gauges are able to capture fog water regardless of wind direction. The collection surface of the JUV gauge is a simple, stamped aluminum sheet (which is standard), whereas that of the WH gauge consists of nylon strings positioned 2 mm apart. This configuration worked well for our páramo conditions, and its construction costs were low. However, we did not study whether different string separations on the WH gauge would affect water collection. On the other hand, calibrations of our equipment, corrections for wind direction and the laser disdrometer data to identify other precipitation different than fog, allowed to minimize the impact on our estimations. It is important to highlight our setup lacks a spectrometer; then fog could be underestimated due to evaporation losses, short events or the fog thickness. In our case, performance is not related to the ecosystem, but it would be related to the climate; whether it is drier and windier (not necessarily stronger, but more constant), it would affect drying the water droplets from the mesh, etc. Given the scarcity of studies comparing different types of fog gauges—especially for páramos—and the fact that all of our fog gauges worked satisfactorily, we are confident that our results provide new insights.

2.4.3 Frequency of cloud water occurrence in the Andean páramo

During the 365 days of monitoring at our site, fog occurred on 249 days (68%). On only three of those days was fog present without any other type of precipitation; all the other days were characterized by fog combined with another type of precipitation (drizzle, light rain, rain or heavy rain). For comparison, Montecinos et al. (2018b), working in a semiarid zone in Chile, reported that 53.7% of the days of the year were foggy; García-Santos & Bruijnzeel (2011) reported that in a subtropical ridge-top cloud forest, fog-only days accounted for 49% of all days with some form of precipitation and Bittencourt et al. (2019), working in a Tropical Montane Cloud Forest, reported fog occurrence on 64% of days. At our site, during the days that fog occurred with another type of precipitation the fog gauges recorded on average 1.37 mm day^{-1} (1.48 mm day^{-1} by the JUV, 1.39 mm day^{-1} by the WH and 1.22 mm day^{-1} by the FS). These amounts are similar to the 1.53 mm day^{-1} (JUV gauge) and 1.27 mm day^{-1} (WH gauge) reported by Regalado & Ritter (2017) for an exposed site in Tenerife, but they contrast with the higher values reported by Montecinos et al. (2018b), with a mean value of 2.9 mm day^{-1} at their Chilean site, and by Estrela et al. (2008), with values of 2.0 and 7.0 mm day^{-1} in two mountainous locations.

Overall, our results indicate that fog and drizzle are the major sources of water to páramo vegetation, especially during late night- time and early mornings. In terms of water input, we have more fog input during the night and early morning when evaporation is low, and during the daylight, we have more inputs from rainfall, according to Brauman et al. (2010), solar radiation is blocked more efficiently by rainfall clouds than foggy conditions; thus rainfall, prevents evaporation better than fog during the daylight. Although fog occurs at any time of the day at our site in the Andean páramo, it is most common in the early morning and at night (Figure 2.8). A similar distribution was observed by Regalado & Ritter (2017) at their Tenerife site, as well as by Obregon et al. (2011) in a tropical lowland forest. Páramo vegetation has many adaptations to cope with variable temperatures and intercept water vapour (Helmer et al., 2019). We hypothesize that the more intense fog observed during these periods is able to condense and reach the soil, increasing its soil moisture content—and in this way, fog water could be an additional source of water for the tussock grasslands in the páramo. According to Ochoa-Sánchez et al. (2020), quantification of fog is needed to provide a better understanding of the evapotranspiration process.

Overall, this study furthers the advances of our understanding of the importance of fog to páramo ecosystems and establishes the basement for coming studies on climate change and its effects on the hydrology, notably, the water yield from these ecosystems in the Andes. Further work is needed to quantify the contribution of fog to the water used by vegetation and to elucidate the ecohydrological role of fog.

2.5 Conclusions

The aim of our study was to assess the performance of three types of fog gauges in the Andean páramo. We compared the fog-collection capabilities of two cylindrical gauges and two flat-screen gauges, taking into account the effects of wind speed, fog rates and duration of fog events. In addition, we also focused on the quantification of fog during events consisting of fog only (FO) and of fog with other types of precipitation, classified as fog dominant (FD), fog non-dominant (FND) and fog negligible (FN); and we analysed fog and rainfall occurrence on a daily basis.

Because the use of a single flat-screen fog gauge oriented in one direction could result in biased output, we installed two flat gauges, using historical wind-direction data to accurately orient them (facing in the two predominant wind directions at our study site). Installation of the flat-screen gauges was more challenging than that of the cylindrical fog gauges, requiring a series of corrections for wind direction.

The cylindrical wire harp gauge and the flat screen panel were the most affected by wind speed, which resulted in more fluctuations in collection, especially for fog events combined with other types of precipitation. In terms of collection the flat-screen gauge was lower than that of the cylindrical gauges except in the case of FO events, when the surface contact area of the flat-screen gauge gave it a better capacity to collect fog. Overall, both cylindrical fog gauges showed a better performance, which suggest that any type of cylindrical collector is suitable for the climatic páramo conditions. The Juvik and Wire harp collectors showed similar collection effectiveness. Since the Juvik type collector has been used worldwide in many ecosystems, for the analyses in chapter 3 and chapter 4, we considered using data derived from the cylindrical Juvik fog gauge.

In this páramo, fog is very frequent and primarily occurs combined with drizzle and light rain. During our 365-day study period, fog occurred on 269 days, mainly in the early morning and during the night. At these particular times of the day, the amount of fog can exceed the amounts of drizzle and light rain. Overall, the FO events are of short duration (< 3 hours) and low rates (< 0.2 mm h^{-1}), and the FD, FND and FN events are of longer duration but fog intensity not exceeding 1mm h^{-1}. The average daily rate of fog water measured was 1.37 mm day^{-1} considering days with fog presence. Rainfall registered by the high-resolution laser disdrometer was 1,200.1 mm, and the fog gauges collected 340.1 mm—suggesting that cloud water flux accounts for a potentially important water input of 22%. Clearly, this potential needs to be further explored. As this is the first study to compare different types of fog gauges in the Andean páramo, our findings represent a significant contribution to the knowledge of both fog collection and the performance of different fog gauges to evaluate water inputs to the ecosystems. Future work should also focus on evaluating the importance of fog to overall ecohydrology of these ecosystems.

Chapter 3

3 Contribution of fog deposition to soil moisture

Páramos are particular ecosystems of the Tropical Andes, where fog and low-intensity rainfall such as drizzle are commonly frequent—but the contribution of these water sources to soil water replenishment and discharge is not yet clear, mainly because the development of techniques for separating fog from drizzle and wind-driven rainfall has been challenging. Fog was measured with a cylindrical Juvik gauge and types of precipitation other than fog with a high-resolution disdrometer. Soil moisture was measured at 100 mm depth by means of Water Content Reflectometers, then Effective precipitation (EP) was calculated. We categorized events as two types: fog only (FO) and fog dominant (FD). We found that in the case of FO events, only small amounts reached the soil (EP ranged between 0.1 and 0.2 mm); in contrast, greater amounts of EP originated from FD events (maximum value of 4.3 mm). Although we found that FO events are negligible for stream water contribution; they are ecologically important for maintaining high relative humidity, low net radiation, and consequently low evapotranspiration rates. Our research provides new insights into the hydrological role of fog, enabling us to better understand to what extent its input influences the water resources of the Andean páramo.

Related publication

Berrones, G., Crespo, P., Ochoa-Sánchez, A., Wilcox, B. P., & Célleri, R. (2022). Importance of Fog and Cloud Water Contributions to Soil Moisture in the Andean Páramo. *Hydrology*, *9*(4), 54. https://doi.org/10.3390/hydrology9040054

3.1 Introduction

The tropical Andes extend over approximately 1.5 million km^2, running from 11° N to 23° S, and include peaks topping 3,500 m.a.s.l, steep slopes, valleys, and plateaus (Josse et al., 2011). They encompass a variety of ecosystems—montane forests, páramo grasslands, wetlands, glaciers (Schoolmeester et al., 2016)—that exhibit complex interactions among species and between species and their environments (Young et al., 2011). As a result of the advection of clouds, these mountains are commonly covered in fog (Walmsley et al., 1996), the intensity and frequency of which affect water inputs and outputs (Aparecido et al., 2018), thus playing an important ecological and hydrological role. At high elevations, fog transported by wind deposits liquid water droplets on plant canopies that then seep down to the soil surface (Delay & Giambelluca, 2011; Katata, 2014).

Herein, we define as fog-only (FO) events those that are 100% fog; and as fog dominant (FD) events those consisting of fog combined with drizzle and/or light rain, but fog is the major contributor (percentages between 50% and 99%) (Berrones et al., 2021). Montane grasslands and shrublands known as páramos, found above the tree line in the upper region of the northern Andes, are characterized by low temperatures and high radiation (Wright et al., 2017). They are home to distinct plant communities (Josse et al., 2011), dominated by tussock grasses and cushion plants with forest patches (*Polylepis* sp.) growing along water streams. The main soil types are Andosols and Histosols. The wet and cold climate favor organic matter accumulation. This, together with the volcanic ash accumulation is responsible for the dark, humic and acid soils, with an open pore structure (Crespo et al., 2011). The vast capacity of páramo soils to store water and buffering capacity are other important features (Buytaert et al., 2005; Young et al., 2011). In these natural grasslands, evapotranspiration rates are relatively low since the frequent presence of fog—in addition to the cloud cover presence, high relative humidity, and low temperatures—results in low transpiration rates (Buytaert et al., 2011).

Several studies have found that cloud water deposition represents an important water input for tropical montane cloud forests (Bruijnzeel, 2001; Katata, 2014), and in the Andes it additionally makes a valuable contribution to the regional water supply (Bendix et al., 2006). The water input through fog deposition in páramo tussock grasslands is less well understood since this function is related to regional climate (Ingraham et al., 2008). Only a few studies have focused on fog water input in the Andean páramo (Berrones et al., 2021; Cárdenas et al., 2017; Tobón & Gil Morales, 2007); and although Cárdenas et al. (2017) assessed the contribution of occult precipitation (fog and drizzle) to soil moisture, there is still insufficient data showing whether FO water reaches the soil, thereby increasing soil moisture. The paucity of such data is mostly due to the lack of appropriate instrumentation and the technological challenges of separating fog from drizzle and wind-driven rain. Overcoming this obstacle is a primary need, because better understanding of the hydrological role of fog in the Andean páramo is essential for accurately estimating the water balance. Previous attempts to quantify fog water deposition have been based on various methods, including measurement of net precipitation (Bruijnzeel et al., 2005), modeling of fog water deposition (Katata, 2014; Katata et al., 2010), measurement of increases in plant weight when exposed to fog (Chang et al., 2002; Tobón & Gil Morales, 2007), and the eddy covariance method (Eugster et al., 2001; Holwerda et al., 2006; Schmid et al., 2011).

The availability of water for plants and for soil–plant–atmosphere transfer processes is determined by soil water content (Famiglietti et al., 1998; Tobón, 2021). In the Andes, the high organic matter content of the soils gives them a strong water regulation capacity. To what extent fog water deposition contributes to soil moisture dynamics has been studied mostly in forested regions, less so in grasslands (Ingraham et al., 2008; Ingraham & Mark, 2000). Fischer et al. (2016) estimated fog drip in pine forests, showing that its effects on soil moisture helped maintain tree functions such as leaf–water relations, sap flux dynamics, and growth rates. Similarly, Eugster et al. (2006) showed that in elfin mountain cloud forests, inputs from fog water deposition—although not a very large component of the hydrological budget—were nevertheless considerable. In the tropical Andean cloud forests of Colombia, Tobón (2021), working at three sites, showed that soil moisture remained close to field capacity and saturation owing to low intensity rainfall— including fog events—and the high organic matter content. With respect to grasslands, Ingraham & Mark (2000) found at a New Zealand site that fog intercepted by tussock grasses represented a substantial contribution to the water yield.

While the question of fog water contribution to the hydrological system has been addressed in various environments, much uncertainty still exists regarding fog drip and soil moisture gains due to fog in the tussock grasslands of páramos. For this reason, our work focuses on the analysis of FO and FD events, to assess whether the water intercepted by the vegetation is able to reach the soil. The three primary aims of this study were (1) to ascertain to what extent water deposited through FO events can contribute to soil moisture; (2) to evaluate whether water deposited through FD events reaches the soil; and (3) to analyze meteorological conditions or variables related to soil water content changes.

3.2 Materials and Methods

3.2.1 Instrumentation

The Zhurucay Ecohydrological Observatory encompasses a monitoring super-site located in a hillslope at 3,770 m.a.s.l. equipped with a variety of instrumentation, including (1) a meteorological station that records variables such as solar radiation and long- and short-wave net radiation (Campbell Scientific CS300 Apogee pyranometer), wind velocity and direction (CNR2–Kipp and Zonen Met-One 034B Windset anemometer), atmospheric pressure (Vaisala barometer PTB110), and air temperature and relative humidity (Vaisala thermometer/hygrometer HMP155 with a radiation shield); (2) CS616 Campbell Scientific Water Content Reflectometers (WCRs) installed horizontally at the hillslope-top, at a soil depth of 10 cm and 4 m apart, to measure soil water content. There is no lateral flow at the measurement site. WCRs accuracy is 2.5% with standard calibration, whereas resolution and precision are better than 0.1%; (3) a laser disdrometer (Thies Clima Laser Precipitation Monitor [LPM] 5.4110.00.000 V2.4 × STD, with a resolution of 0.01 mm), which measures the size and fall velocity of drops and is well suited for the detection of different types of precipitation (e.g., drizzle, rain, and mixed precipitation); (4) a tipping-bucket rain gauge (RG) (Texas Electronics tipping-bucket TE525MM, with a resolution of 0.1 mm); (5) a cylindrical modified Juvik fog gauge (FG) (dimensions 40.5 cm high, 14 cm outer diameter, 567 cm2 cross-sectional area) having a louvered aluminum shade screen collection surface with a 50-cm-diameter protective cover and two plastic funnels—one underneath the screen and one underneath the tipping-bucket rain gauge, which in turn is connected to a bucket via a plastic pipe to drain the collected water; the tipping-bucket rain gauge and the bucket were covered with plastic to avoid vertical precipitation. To estimate the cloud water flux, the FG effective capture area was defined as the projected capture area (cylinder diameter × height).

In a prior study (Berrones et al., 2021), we measured cloud water interception with different passive fog collectors—two cylindrical types (Juvik and Wire Harp) and two flat-screen types—oriented to the two main wind directions. Our results showed that for our study site, cylindrical Juvik type FG performed the best, yielding better fog and cloud water estimations. For this reason, all the analyses for the current study were done with this FG. All of the variables (e.g., fog, rainfall, volumetric water content, meteorological variables) were continuously recorded at 5-min intervals from September 2017 to December 2019. Weather conditions during the study period are shown in Figure 3.1.

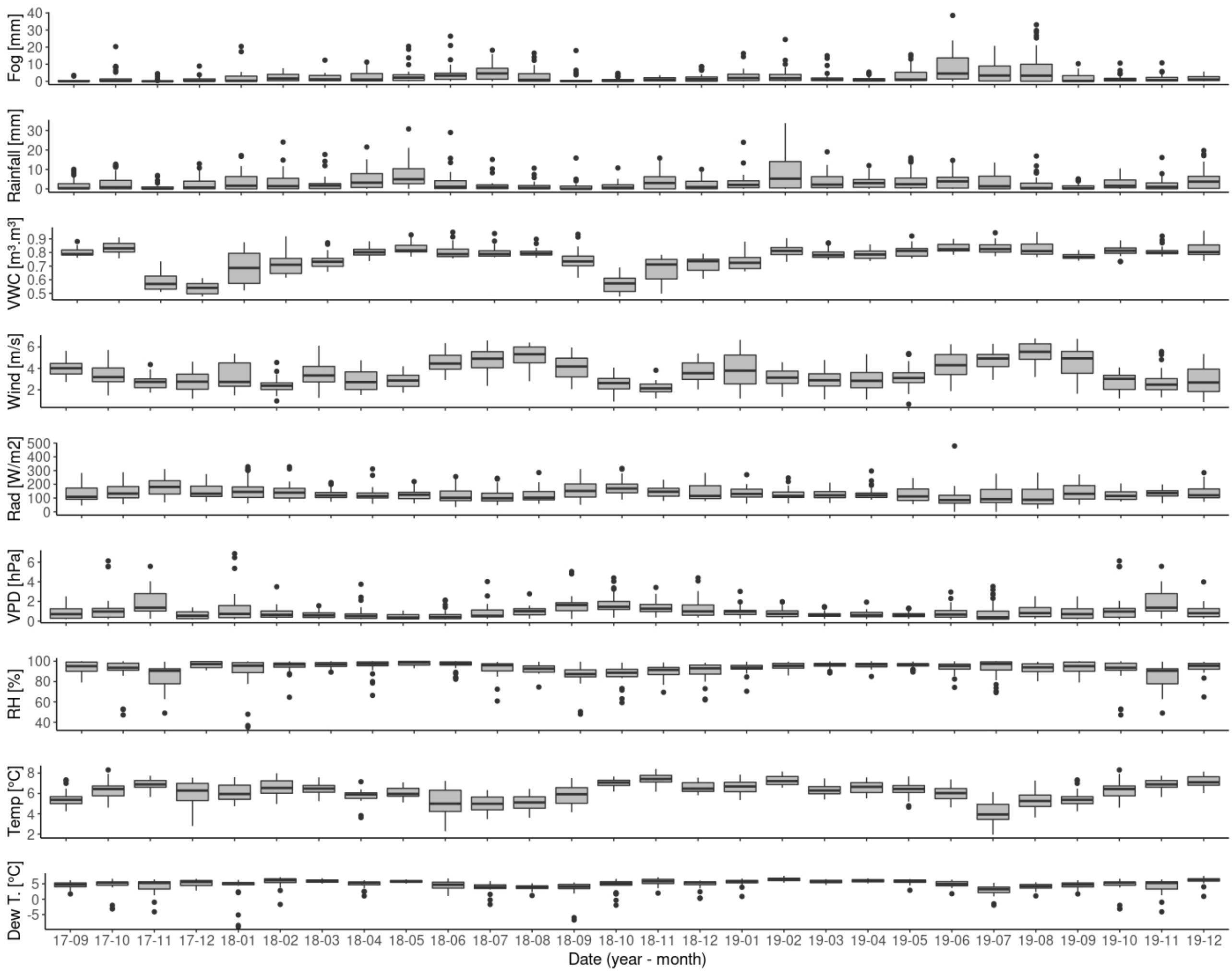

Figure 3.1: Fog input, precipitation, volumetric water content (VWC), and meteorological variables for the study site during September 2017 to December 2019.

3.2.2 Selection of events and determination of Effective Precipitation

For our analysis, we selected FO and FD events lasting longer than 10 min and separated by 4 hours (according to Ochoa-Sánchez et al. (2018), this time gap allows for the assumption that tussock grass leaves have dried before the next event). As noted earlier, we characterized each event as one of two types: (i) Fog-only (FO) events, defined as those captured by the FG but not by either the LPM or the RG (i.e., the event consisted of 100% fog); and (ii) fog dominant (FD) events, defined as those for which the water collected by the FG was greater than the amount recorded by the LPM and the RG (i.e., the fog proportion of the total collected was between 50% and 99%). In addition, to reduce the bias due to wind-driven precipitation, all the FD events with wind speeds higher than 4 m s^{-1} were excluded from the study (Berrones et al., 2021). To measure volumetric water content (VWC) in cubic meter per cubic meter with the CS616 WCR output period (P) in microseconds, a calibration curve shown in Equation 2.1 was developed for this site, as described in Ochoa-Sánchez et al. (2018):

$$VWC = 0.0037\,P^2 - 0.1949\,P + 2.9257 \qquad (2.1)$$

For a more detailed information about the calibration procedure, the reader is referred to supplementary material in Ochoa-Sánchez et al. (2018). In order to obtain a data set that shows which events reached the soil, we included only events that met the following criteria: (1) VWC remained at a minimum (0.01 m^3 m^3) or did not change for at least 2 hours before the event; (2) VWC increased during the event, caused by a water input from drizzle, light rain, and/or high-intensity fog; and (3) the change in VWC during the event had a value higher than the precision and resolution of the WCR (0.1% VWC). These criteria rule out interference from other processes, such as lateral flows.

To calculate the change in soil water storage (SWch), we multiplied the increase in VWC (recorded by the average of two WCRs) over the course of the event by the installation depth of the sensor (10 cm). For the purposes of this study, we use the term effective precipitation (EP) to represent the amount of increase in SWch. Thus, each event was further classified according to EP: Class I for FO and FD events with EP (i.e., SWch > 0 mm) and Class II for FO and FD events without EP, (i.e., SWch = 0 mm). This classification yielded 30 Class I events (9 FO and 21 FD) and 52 Class II events.

3.2.3 Identification of events Consisting of fog and rainfall combined

To determine what other type(s) of precipitation (drizzle, light rain, rain, heavy rain) occurred in combination with fog during the FD events, we used the LPM, which is highly sensitive to small drops. Its data telegram generates a matrix that provides the number of drops detected at 22 different drop sizes (from 0.125 to 8 mm) and at 20 different velocities (from 0 to 10 m s^{-1}). First, we obtained the number concentration of raindrops per unit volume per unit size—N(D)—from the LPM counts using Equation 2.2, where *N(Di)* is the number concentration in ith size class (mm^{-3} mm^{-1}), *Di* is the mid-size diameter of the ith class (mm), *A* is the cross-sectional area of the sensor (m^2), *t* is the measuring time (seconds), *nij* is the number of drops within the ith size and jth velocity class, and *Vj* is the fall speed of the jth velocity class (m s^{-1}).

$$N(Di)=\sum_{j=1}^{20}\frac{nij}{AtVj\,\Delta Di} \tag{2.2}$$

Then, we calculated the mean volume diameter *Dm* (mm) at 5-min intervals from a normalized distribution. In Equation 2.3, *N(D)* is the drop size distribution, *D* is the particle diameter, and D^3 and D^4 are the third and fourth moments calculated for each spectrum.

$$Dm=\frac{\int_0^{\infty} N(D)\,D^4\,dD}{\int_0^{\infty} N(D)\,D^3\,dD} \tag{2.3}$$

According to Orellana-Alvear et al. (2017), working at the same study site, the 0.1 < Dm [mm] ≤ 0.5 corresponds to drizzle, the 0.5 < Dm [mm] ≤ 1.0 corresponds to light rain, the 1.0 < Dm [mm] ≤ 2.0 corresponds to rain, and the Dm [mm] > 2.0 is defined as heavy rain. On that basis, we calculated the amounts of different kinds of precipitation for each of the FD events (independently of whether they had been classified as Class I or Class II). To identify what type of precipitation commonly reaches the soil, we used a bar plot for the Class I events; and to observe how fog and cloud water depth relate to EP, we calculated the percentages of fog and of other kinds of precipitation for each of the 82 events, then used them to construct a scatter plot.

3.2.4 Relationship between Effective Precipitation and meteorological variables

To determine how EP amounts might be influenced by climatic variables and by the various types of precipitation, we plotted the following variables using scatter plots and heat maps: EP amounts; fog depth, drizzle, light rain, and rain; intensity of events; duration of events; mean wind speed, relative humidity, radiation, temperature, dew temperature, and vapor pressure deficit. A linear model and Pearson correlations were performed to analyze the independence of EP and meteorological variables. All these analyses were coded in R x86_64-pc-linux version 3.6.3 software using the lubridate, dplyr, ggplot2, stringr, reshape, psych, corrplot, and heatmap packages.

3.3 Results

3.3.1 Selection of events and determination of Effective Precipitation

From the dataset, 82 events were selected for analysis: 45 FO events and 37 FD events. Of these, 30 were designated Class I (effective precipitation > 0 mm) and 52 were designated Class II (effective precipitation = 0 mm). Figure 3.2 shows an example of each classification for each event type, four hours pre event and after event were plotted to observe that changes in volumetric water content are due to the water input during the event and not for other prior events nor by lateral flow processes. Table 3.1 summarizes the main characteristics of the FO and FD events and the calculated effective precipitation for each. Even though the FO events outnumbered the FD events, their total duration was around three times shorter. The combined total depth from the FO and FD events was 146.6 mm, of which 21.5 mm (15%) reached the soil as EP. Total EP consisted of 57% from the FD events but only 20% from the FO events. The composition of the FD events' total depth was 69% fog, 17% light rain, and 14% drizzle.

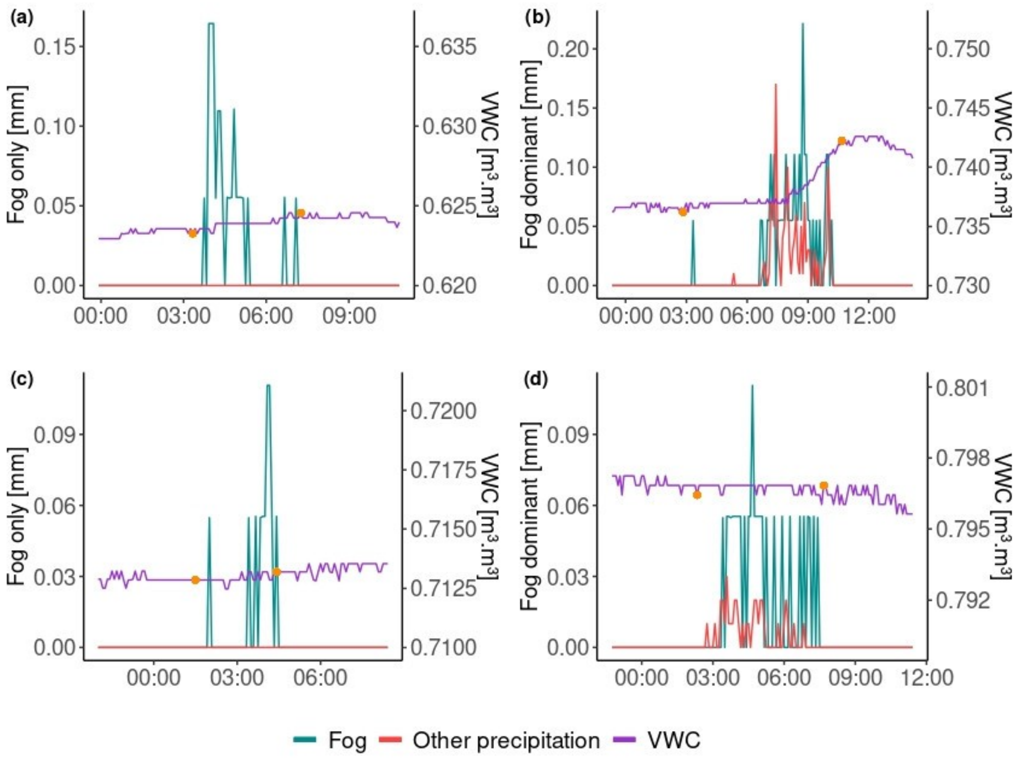

Figure 3.2: Some examples of the eighty two fog-only and fog-dominant events and their corresponding soil volumetric water content (VWC) plotted considering four hours before and after the event. The orange dots represent a reference for the start and the end of the event, to calculate the change in VWC: (a) event 23, Class I event (producing an increase in VWC) (b) event 19, Class I event (producing an increase in VWC); (c) event 59, Class II event (producing no increase in VWC), and (d) event 40, Class II event (producing no increase in VWC).

Table 3.1. Characteristics of fog-only and fog-dominant events. Values of volumetric water content and meteorological variables are the mean value for each type of event independently they belong to Class I or Class II.

Variable	**Type of event**	
	Fog Only	**Fog Dominant**
Number of events	45	37
Duration of events (hours)	77	215
Total depth (mm)	24.4	122.2
Fog (mm)	24.4	83.9
Drizzle (mm)	0	17.3
Light rain (mm)	0	20.3
Rain (mm)	0	0.7
Heavy rain (mm)	0	0.03
Number of events Class I (EP > 0 mm)	9	21
Number of events Class II (EP = 0 mm)	36	16
Effective precipitation (mm)	1.1	20.4
VWC (m^3 m^3)	0.7	0.7

Wind speed (m s^{-1})	3.1	2.7
Vapor Pressure Deficit (hPa)	0.6	0.2
Relative Humidity (%)	95.8	99.7
Temperature (°C)	4.1	5.3
Dew Temperature (°C)	3.4	5.2
Radiation (W m^{-2})	21.9	18.1
Radiation (MJ m^{-2})	0.05	0.14

VWC = Volumetric Water Content

3.3.2 Identification of events consisting of Fog and Rainfall combined

Figure 3.3 shows the total depth for the 30 events that reached the soil, as well as the composition of the FD events. The Class I FO events yielded between 0.1 and 3.1 mm of fog water, whereas the yield of the Class I FD events included between 0.3 and 11.3 mm of water from fog. Drizzle and/or light rain were the most common types of precipitation that contributed to soil moisture increase: half the FD events contained between 5 mm and 16.8 mm, while the other half contained less than 5 mm.

Effective precipitation, measured as an increase in VWC, ranged from 0.1 to 0.2 mm for all Class I FO events. Similarly, for Class I FD events, EP ranged from 0.1 to 0.3 mm, with fog accounting for over 90% of the total (Figure 3.4). For cases in which the fog proportion was lower (70%–80%) and the drizzle and light rain proportion was higher, EP was also higher—0.3–2.2 mm; and for cases in which the fog proportion was lower still (50%–70%) with even higher amounts of drizzle and light rain, EP rose as high as 4.3 mm. In other words, the FD events with relatively higher EP (over 1 mm) were those having relatively lower percentages of fog and a higher total depth (over 5 mm). We can infer, then, that EP increases with total amount per event and with greater proportions of drizzle and light rain rather than fog.

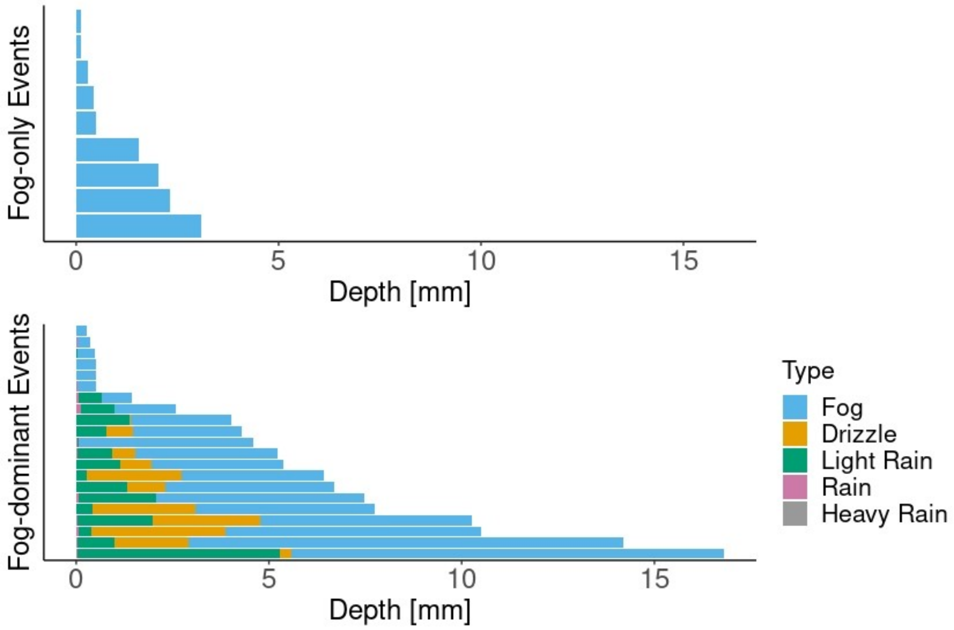

Figure 3.3: Total depth for the nine fog-only and the 21 fog-dominant events that produced effective precipitation (Class I), and composition of cloud-water events.

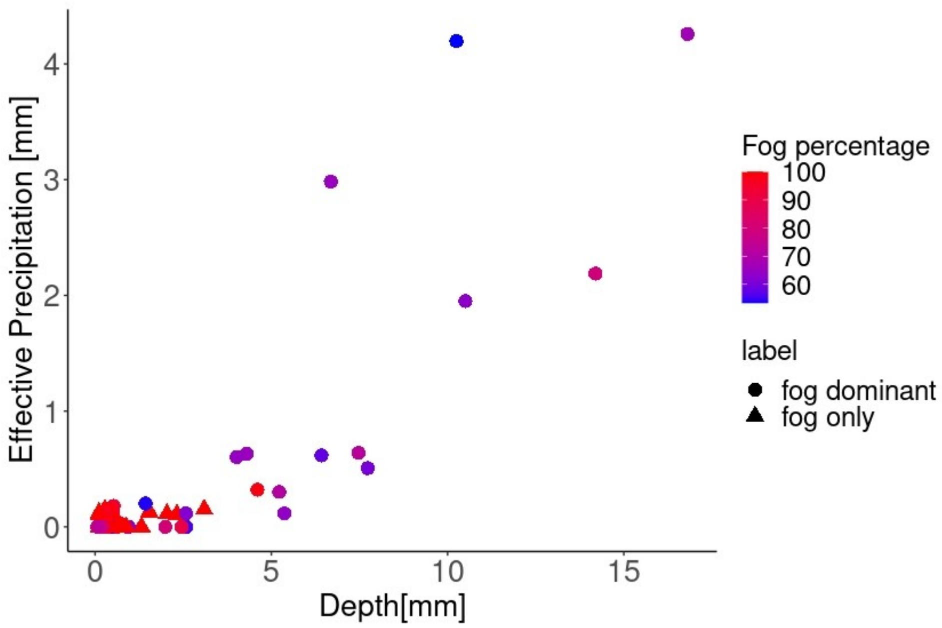

Figure 3.4: Relationship between events depth and effective precipitation.

3.3.3 Relationship between Effective Precipitation and meteorological variables

The FO and FD events were plotted on heat-maps in ascending order of their EP amounts, together with the mean values of total depth, duration, and intensity of the events, as well as the available meteorological variables (wind speed, air temperature, dew temperature, relative humidity, radiation, and vapor pressure deficit, see Appendix A). For both FO and FD events, duration, intensity, and total event depth were directly related with increasing EP. Figure 3.5 shows the linear regression for EP and meteorological variables, the coefficient of determination and p-value from the regression indicate a poor fit of the model; values of $R^2 < 0.1$ were obtained for all the meteorological variables assessed. In addition, Pearson correlation for the same variables showed low coefficients < 0.2 (Figure 3.6); which demonstrates that EP and the considered meteorological variables are not linearly related.

For both FO and FD events, the most important event characteristics related to EP were duration and depth; these are shown in Figure 3.7, plotted against EP. The FO events—of which 44% lasted less than 1 hour and 56% lasted from 1 to 8 hours—produced little EP. For the Class II FO events duration was highly variable and did not show any pattern; for the Class I FO events, at least 1 hour was needed for water to reach the soil. The FD events produced considerably more EP—as high as 4.25 mm for an event of 14 hours' duration and depth of over 10 mm. Even though the Class I FDW events showed higher EP values overall, they varied widely in both duration and depth. In the páramo, events lasting more than 13 hours and yielding more than 10 mm are potentially important in the hydrological cycle, because of their higher EP. The four events in this category during our study consisted mainly of fog combined with drizzle and light rain (Figure 3.7), in the following amounts as measured by the instrumentation: fog = 11.3 mm, 11.2 mm, 6.6 mm, and 5.5 mm; drizzle = 1.9 mm, 0.3 mm, 3.5 mm, and 2.8 mm; and light rain = 1 mm, 5.2 mm, 0.4 mm, and 1.9 mm.

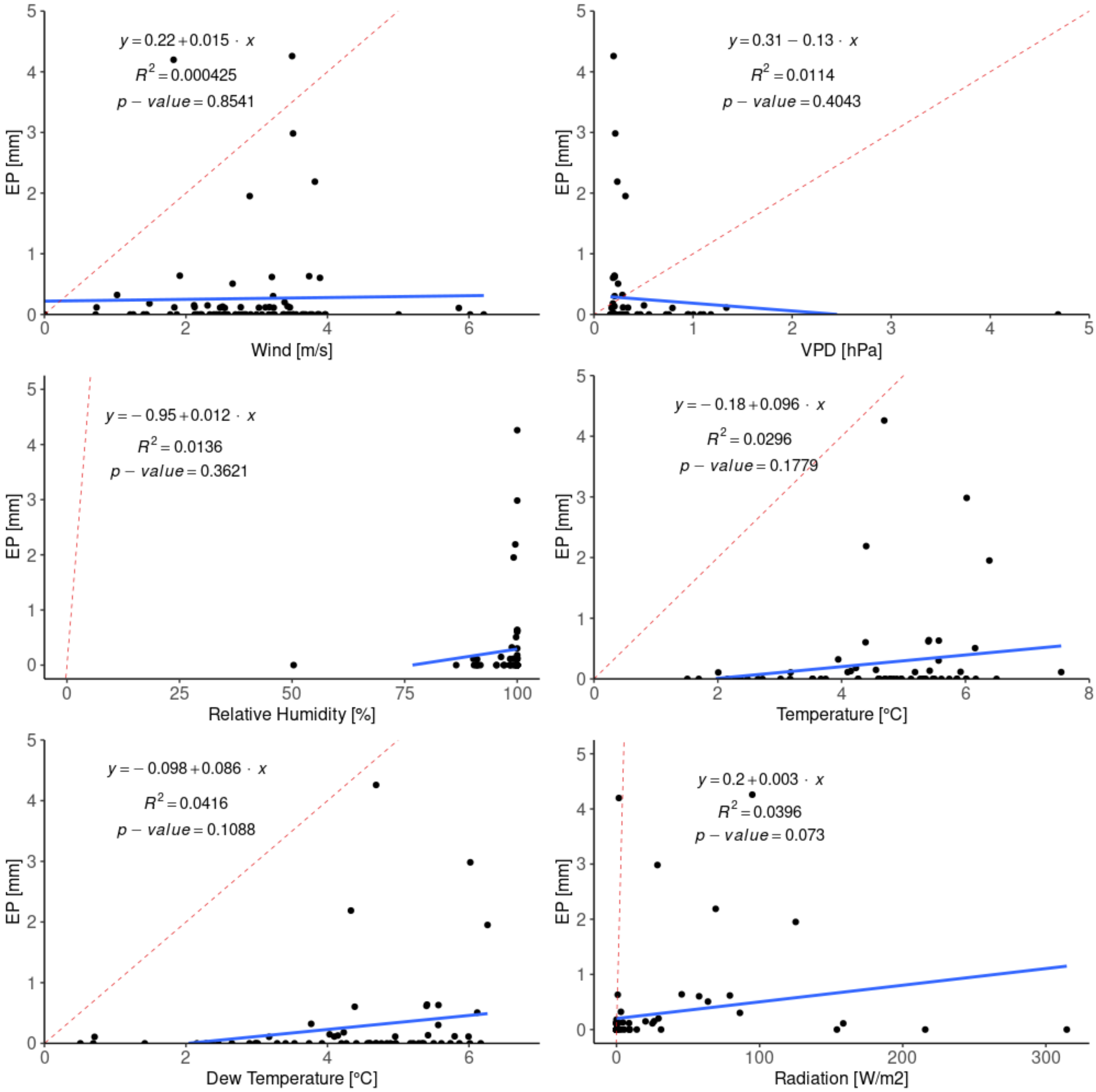

Figure 3.5: Effective precipitation (EP) versus meteorological variables for the two types of events fog-only and fog-dominant (black dots), with the corresponding coefficient of determination, where the blue line represents the linear regression model and the red line is the identity line (slope = 1).

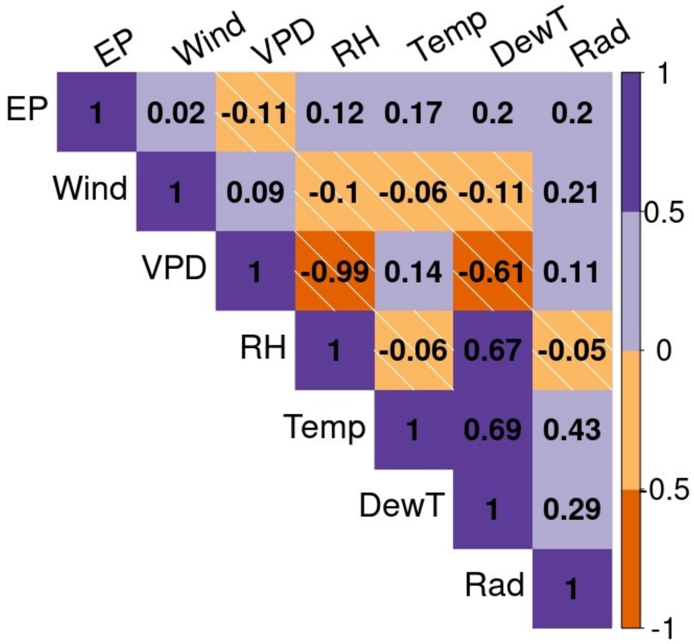

Figure 3.6: Effective precipitation (EP) versus meteorological variables for the two types of events fog-only and fog-dominant, with the corresponding correlation coefficient

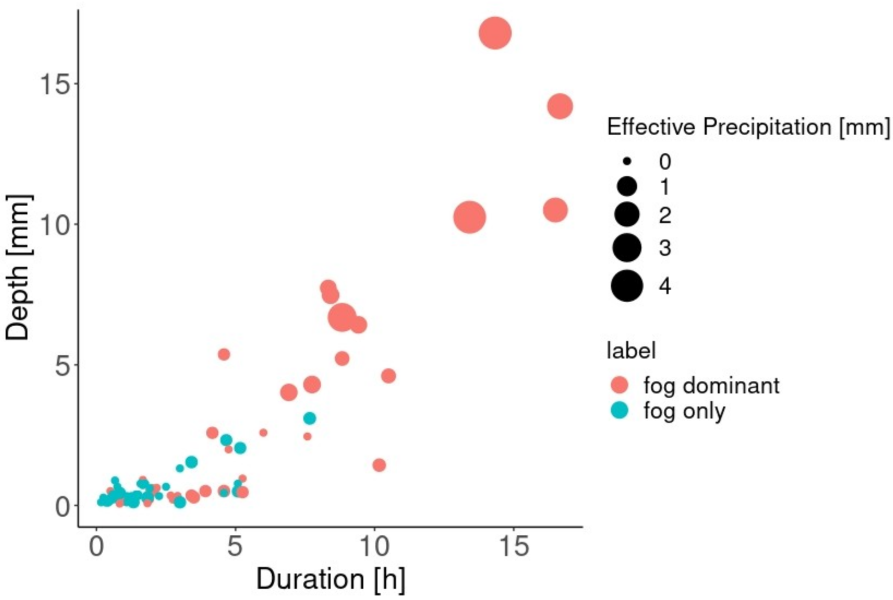

Figure 3.7: Relationship among duration, total event depth and effective precipitation for the 82 events.

3.4 Discussion

3.4.1 Quantification of Effective Precipitation

As shown in Table 3.1, of the 146.6 mm total water yield from the 82 FO and FD events we analyzed, 15% became EP (added to soil moisture). In Table 3.2 we compare our results with findings from other ecosystems (even though the methodologies used for these other studies varied, the estimations obtained are useful for understanding the importance of fog- and fog combined with other precipitation contributions to soil moisture). During our 26-month study, only a small percentage of the total water collected from the FO events ended up reaching the soil (1.1 mm, or 4.5%)—suggesting that in the Andean páramo, fog water contribution to the net hydrological input is negligible. Fleischbein et al. (2006), working in montane forests in Ecuador, reported also negligible fog water inputs. In contrast, the studies of Clark et al. (2014) and Liu et al. (2004) for cloud and rain forests respectively, found higher values—the latter showing an average annual fog contribution amounting to about 5% of annual rainfall at a site in southwest China.

Soil moisture is measurably higher beneath tree canopies (Liu et al., 2005), but fog inputs also depend on the density and frequency of fog (Tobón, 2021). Despite the high frequency of fog in the Andean páramo, days with FO and no precipitation are rare (Berrones et al., 2021), and most of the FO events that reached the soil occurred in the early morning, when evaporation is low. In these grasslands, fog water is intercepted by the tussock leaves, diminishing water input to the ground, although the water storage capacity of tussock grasses (approximately 2 mm) (Ochoa-Sánchez et al., 2018) is smaller than that of forests, which have more complex canopies (Ramírez et al., 2017). Variations in fog drip are affected by the type, size, location, and density of the foliage (Goodman, 1985). In the páramo, the low intensity of fog is not sufficient to saturate the tussock grasses leaves; causing no drip. On the contrary, in forests, their denser foliage allows capturing more fog water.

The amount of water collected from FD events was higher than that from FO events; however, the EP was also low (Table 3.1), accounting for only 17% (20.4 mm) of the total depth (122.2 mm). Our findings are in agreement with those of other studies, e.g., Herckes et al. (2002); Gomez-Peralta et al. (2008), working in cloud forests below 2500 m, where FD input might be insignificant; and Giambelluca et al. (2011a), working in a dry cloud forest where the majority of intercepted water was re-evaporated from the wet vegetation and never reached the ground.

In páramo, soil is constantly saturated, which means soil water content is normally above 80% (Célleri & Feyen, 2009). To study the gain in soil moisture from FO and FD we needed events when soil is not saturated and for this reason, we excluded from our analysis events with soil water content ≥ 80%. Cárdenas et al. (2017) reported gains in VWC in Colombian páramo soils under field capacity conditions, following large occult precipitation events; however, it should be noted that in this study, the contribution of occult precipitation to soil moisture was not separated from that of rainfall.

3.4.2 The Impact of Cloud-Water deposition on Effective Precipitation

The high-resolution laser disdrometer, with its ability to measure small drops, proved to be an effective instrument for monitoring the other types of precipitation that accompany fog during FD events. We determined that (as shown in Figure 3.3) the FD events that resulted in EP consisted mainly of fog combined with drizzle and/or light rain and had a total amount per event ranging from 0.3 to 11.3 mm. In addition, all the events occurred in the early morning; and wind speeds during the events varied between 1.5 and 3.4 m s^{-1}. Since fog water contribution is also influenced by fog density and frequency as well as wind speed (Tobón, 2021), it is plausible that the FD events with low total depth had high fog density and occurred at lower wind speeds.

At higher wind speeds, deposition via impaction increases; for instance, Liu et al. (2004) attributed low fog-drip to the low wind speeds (< 2 m s^{-1}), and Holwerda et al. (2010) reported low amounts of FD in a secondary forest and in a mature cloud forest (about 6% and 8%, respectively, of dry season rainfall) due to low wind speeds. As noted earlier, all the events included in our analysis occurred at wind speeds below 4 m s^{-1} therefore deposition on vegetation by these events was also low despite differences in plant height and complexity of plant leaves between tussock grasses and forests. This hypothesis is supported by previous findings that the most important factors affecting fog deposition rate are fog droplet size distribution (Chang et al., 2006), the topography of the field site (Tav et al., 2018), fog duration, surface area, and geometry of the vegetation (Bruijnzeel et al., 2005).

The FD events having higher percentages of drizzle and light rain recorded the higher amounts of EP (Figure 3.4), suggesting that EP is related to a major presence of drizzle and light rain rather than fog. Since drizzle and light rain droplets are bigger than fog droplets, and their fall velocity is higher, during these larger events it is likely that the tiny droplets of fog were more susceptible to being blown away and dried before deposition on tussock grass leaves. In addition, from field observations we know that fog occurs only intermittently during the day and most of the time is of brief duration, while drizzle occurs frequently enough in the páramo that only 12% of the days are completely dry (Padrón et al., 2015).

3.4.3 Relationship between Effective Precipitation and meteorological variables

None of the meteorological variables analyzed (relative humidity, vapor pressure deficit, wind speed, air temperature, dew temperature, and solar radiation) showed any relationship with EP, for either FO or FD events (Figures 3.5 and 3.6). All the FO events that resulted in EP occurred at relative humidities over 90%, and all the FD events that resulted in EP occurred at humidities higher than 98%. While fog formation generally takes place under high relative humidity—conditions ranging from undersaturated to slightly supersaturated (Gultepe et al., 2007)—relative humidity was not a determinant of EP; FO events occurring at humidities between 80% and 100% resulted in no EP. Similarly, we found no relationship between EP and vapor pressure deficit, dew temperature, air temperature, wind speed or solar radiation, suggesting that meteorological variables are not drivers for EP.

For both FO and FD events, three characteristics did show a direct relationship with EP: duration, total amount per event and intensity (see Appendix A). The duration of FO events varied between 1 hour and 8 hours (Figure 3.7), whereas FD events were longer and with intensities > 0.5 mm h^{-1}, which produced higher amounts of EP. Fog density information was beyond the scope and possibilities of this current study, then we assume that FO events were dense enough to cause fog drip to the ground and resulted in EP despite small total depth.

In the Andean páramo, hydrological regulation capacity might be related to the high frequency of fog and low-intensity rainfall (drizzle). But although it is widely acknowledged that fog plays an important hydrological role in different ecosystems, from our findings we can suggest that fog has an important ecological role in the páramo mainly due to its availability for vegetation—reducing CO_2 uptake, transpiration, and evaporative losses (Célleri & Feyen, 2009); however, its contribution to streamflow is negligible. From a hydrological point of view, inputs from FD are more important. For this reason, water balance studies should focus on observations of low-intensity rainfall rather than fog.

Table 3.2.Studies of fog and cloud-water deposition in ecosystems with different types of vegetation around the world.

Reference	**Ecosystem**	**Location**	**Altitude (m a.s.l)**	**Study period**	**FD Input (mm)**	**FO Input (mm)**	**EP from CW (mm)**	**EP from FO (mm)**	**Method**
This study	Andean Páramo	Southern Ecuador	3,770	September 2017 – December 2019	122.2	24.4	20.4	1.1	Volumetric water content, change in soil water storage
Cárdenas et al. 2017	Andean Páramo	Colombia – Romerales	3,700 – 4,150	7 months	120	-	-	-	Soil moisture content
Clark et al. 2014	Andean tropical montane cloud forest / puna transition	Eastern Andes of Peru	2,805 – 3,195	1998 – 2012	316 ± 116 / year	-	316 ± 116 / year	-	Isotopic mixing model
Gomez-Peralta et al. 2008	Andean tropical montane cloud forest	Yanachaga Chemillén National park Central Peru	2,468 – 2,815	1 year	-	221	-	221	Analysis of the components of precipitation
Chang et al. 2006	Montainous coniferous forest	Northeastern Taiwan	1,650	2003 – 2004	-	328 / year	-	328 / year	Lovett micrometeorologi cal model
Liu et al. 2004	Tropical seasonal rain forest	Southwest China	750	1999 – 2002	-	89.4 / year	-	89.4 / year	Fog drip measurement
Herckes et al. 2002	High-elevation site, Vosges Mountains	Eastern France	1,146	1 year	55.5 / year	-	55.5 / year	-	One-dimensional cloud water deposition model

3.5 Conclusions

This study was initiated to assess the importance of fog-only (FO) and fog-dominant (FD) events in contributing to soil moisture in the Andean páramo. The two types of events were divided into two classes according to whether or not they produced effective precipitation (EP), i.e., increases in soil water storage: Class I = EP > 0 mm; Class II = EP of 0 mm. Hence, we focused on the analysis of Class I events.

The total depth from all the FO events was 24.4 mm, only 4.5% of which reached the soil, whereas for FD events 16.7% of the total depth (122.2 mm) turned into EP. The water yield for the FO events was less than 5 mm per event, the maximum duration was 8 h, and at least 1 h was needed for water to reach the soil. Although FO events make a negligible contribution to streamwater, their presence contributes to the maintenance of high relative humidity and low net radiation rates translating to decreased evapotranspiration rates. In contrast, FD events are potentially important for both soil moisture and streamflow in the Andean páramo, because of their long duration (averaging over 13 h) and high total depth per-event (over 10 mm)—owing to the large proportion of drizzle and light rain.

We found no relationship between EP and meteorological variables (wind speed, air temperature, dew temperature, vapor pressure deficit, solar radiation, and relative humidity) since low coefficients of determination and correlation were obtained. While the contribution of fog water to soil moisture is related to fog deposition on vegetation, these meteorological variables are not determinant factors in the estimation of EP amounts.

Because our study was based on rainfall data from a high-resolution disdrometer as well as fog data from equipment tested for monitoring fog in the Andean páramo, we were able to carry out a comprehensive study of various types of precipitation. We believe that our findings significantly advance our understanding of the hydrological role of fog and cloud water in these environments.

Chapter 4

4 Influence of fog deposition on evapotranspiration rates

Tropical mountain ecosystems, such as the páramos of the Northern Andes, are important areas of early climatic change detection and widely recognized as the water towers for local communities and downstream cities. Here, fog and low-intensity rainfall are very common and key for ecohydrological processes. Although evapotranspiration (ET) represents an important part of the water cycle, the interaction between fog and ET processes is poorly understood for páramo vegetation and water resources availability. The present study reports the effects of foggy (fog-only) and mixed (fog and rainfall) conditions on ET. Combined data from a Juvik type fog collector, a laser disdrometer and an eddy-covariance tower were used to determine the relationship between fog and ET rates. To determine whether significant ET reductions resulted due to fog, we used ET and meteorological conditions of dry days as reference. Foggy days showed daily reductions in ET by 6% and net radiation by 9.2%, owing to its early morning occurrence. Fog combined with rainfall reduced daily ET by 43% and net radiation by 33%. The meteorological variables related with ET reductions were net radiation, relative humidity and wind speed. In the páramo mean annual ET and precipitation are 635 ± 9 mm and 1210 ± 101 mm, respectively; annual ET reduction due to the combination of fog and rainfall is estimated between 153 and 348 mm per year. Our results suggest that the continuous presence of low-intensity rainfall and fog restricts water losses by evaporative demand; thus, these findings contribute to a better understanding of the ecohydrological role of these water inputs in the tropical Andes.

Related publication

Berrones, G., Crespo, P., Carrillo-Rojas, G., & Célleri, R. (2022). Fog and rainfall influence on evapotranspiration variability in the Andean páramo tussock grasslands. *Journal of Mountain Science*, *in review.*

4.1 Introduction

Tropical mountainous ecosystems are of high ecological value, where water and energy budgets are crucial on regional and global scale (Klemm et al., 2006). Because mountains represent unique areas for the detection of climatic change and the assessment of climate-related impacts (Beniston, 2003), it is necessary understand the environmental factors that control the surface water balance (Ochoa-Sánchez et al., 2020). One of the important components in the water cycle is evapotranspiration (ET), which significantly influences physical, chemical, and biological processes (Zhang et al., 2022). ET is an important process in the energy transfer from different surfaces to the atmosphere via turbulence (Wang & Dickinson, 2012; Wang et al., 2021), and a key process in the earth's energy budget (Beiderwieden et al., 2008). ET globally accounts for 80% of the turbulent energy transfer (i.e., latent plus sensible heat flux) from earth to the atmosphere (Chapin et al., 2012) and includes evaporation from soil, evaporation from water intercepted by vegetation and transpiration (Ochoa-Sánchez et al., 2020).

The tropical mountains in the Andes encompasses a variety of ecosystems including páramos, that exhibit complex interactions among species and between species and their environments (Young et al., 2011). Low ET rates in páramos are related with low air temperatures and net radiation incidence, high relative humidity and cloud cover (Aparecido et al., 2018; Célleri & Feyen, 2009). This ecosystem has a hydrological regulation capacity, that in part might be related to the high frequency of fog and low-intensity rainfall (drizzle) (Berrones et al., 2022). The climate is humid and cold, and the vegetation is characterized by the presence of tussock grasses and cushion plants with forest patches (*Polylepis* sp.) growing along water streams and in isolated patches. Tussock grasses ET is relatively low; Carrillo-Rojas et al. (2019) and Ochoa-Sánchez et al. (2019) reported values of 1.7 mm/day, which is due to a combination of low temperature and frequent occurrence of cloud cover, mist, and fog (Célleri & Feyen, 2009).

The high frequency of drizzle and cloud water –including fog– in these mountains are important water sources for vegetation, playing a key role in ecohydrological processes. Depending on wind speed, fog liquid water content, droplet size and canopy architecture, cloud water can be intercepted by canopy (Bittencourt et al., 2019); the capacity of the canopy to intercept and store water depends particularly on the surface area of leaves and differs among ecosystems (Chapin et al., 2012). In the páramo for small precipitation events, 80% of the precipitation can be intercepted by tussock grasses (Ochoa-Sánchez et al., 2018). The deposition of this cloud water onto vegetation leaves forms a thin film and it is retained as leaf surface water; then, it may drip to soil surface or re-evaporate into the atmosphere (Eugster et al., 2006; Katata, 2014; Klemm et al., 2006). Fog and cloud water incidence strongly reduce the incoming short-wave radiation, limiting the energy available for ET (Beiderwieden et al., 2008; Klemm et al., 2006). Moreover, both high relative humidity and decreased solar radiation diminish the evaporative demand (Brauman et al., 2010). Relationships between fog incidence and reduced ET in the Andean páramo are poorly understood, hence accurate estimations of fog and actual ET are required to better understand whether fog generates impact on the energy exchange process between land and atmosphere in this ecosystem.

The continuous presence of fog combined with specific environmental conditions (i.e., low temperatures and high relative humidity) reduce plant transpiration and water evaporation (Tobón, 2021). In the Andes most studies have focused on the estimations of ET (Callañaupa-Gutierrez et al., 2021; Carrillo-Rojas et al., 2019; Fleischbein et al., 2006; Ochoa-Sánchez et al., 2020; Ochoa-Sánchez et al., 2019), while other studies have included cloud water interception and ET estimations (Ataroff & Rada, 2000; Clark et al., 2014; Ramírez et al., 2018). However, globally there are few studies that evaluate the ET rates due to fog. For instance, in subtropical montane cloud forests in Taiwan (Beiderwieden et al., 2008; Beiderwieden et al., 2007; Chu et al., 2014), and particularly in the Andes we found only one study in Colombian tropical cloud forests (Tobón, 2021). What we know about ET and fog relation is largely derived from studies conducted in mid-latitude, forested regions; therefore, to our knowledge, no work has been done comparing ET rates under foggy conditions in páramo tussock grasses. We determined fog and rainfall inputs from a passive fog collector and a high resolution laser disdrometer data sets respectively, and actual evapotranspiration using the eddy-covariance method. Therefore, our study aims to close this knowledge gap in the wet Andean páramo by (a) comparing ET rates under fog, mixed conditions (e.g. fog and rainfall) and dry conditions (e.g. no precipitation and no fog), (b) analyzing meteorological variables related with fog conditions that might suppress ET, (c) determining the diurnal pattern of fog occurrence at which ET might be diminished, and (d) establishing the inter-annual variability of ET due to fog.

4.2 Materials and Methods

4.2.1 Instrumentation and data

A super-site is located at the headwaters of Zhurucay at 3,770 m.a.s.l. The Observatory encompasses a variety of sensors to monitor fog, precipitation, meteorological variables and energy fluxes at high temporal resolution. Equipment installed within Zhurucay include: 1) an automatic weather station that records variables such as wind velocity and direction (CNR2–Kipp and Zonen Met-One 034B Windset anemometer), atmospheric pressure (Vaisala barometer PTB110), air temperature and relative humidity (Vaisala thermometer/hygrometer HMP155 with a radiation shield), solar radiation, long and short wave net radiation (Campbell Scientific CS300 Apogee pyranometer); 2) a 3.6-meter eddy-covariance (EC) tower, placed over a 10° slope; measurements of atmospheric CO 2 and water vapor (H 2 O) fluxes were made through an enclosed path infrared gas analyzer (LI-COR Bio- sciences, model LI-7200 IRGA with LI-7550 Analyser Unit, Lincoln, USA). Wind speed and direction with a three-dimensional sonic anemometer (Gill Instruments, model Gill-Wind Master, Hampshire, UK). Net Radiation (Rn) was measured with a 4-component net radiometer (Kipp Zonen, model CNR4, Delft, The Netherlands). High-frequency raw data from turbulent fluxes were processed with the EddyPro software, version 6.2.0 (LI-COR) and averaged to a 30-min blocks. For a more detailed information about EC instrumentation and corrections procedure, the reader is referred to Carrillo-Rojas et al. (2019); 3) a high resolution disdrometer (Thies Clima Laser Precipitation Monitor [LPM] 5.4110.00.000 V2.4 × STD, , 4) a tipping bucket Texas rain gauge (RG) (Texas Electronics tipping-bucket TE525MM, with a resolution of 0.1 mm), 5) a cylindrical modified Juvik fog gauge (FG) (40.5 cm high, 14 cm outer diameter, and 567 cm 2 cross-sectional area). For a more detailed information about fog instrumentation and corrections procedure, the reader is referred to Chapter 2. From a prior study (Berrones et al., 2021) we found that the cylindrical Juvik FG outperformed the other FG installed (i.e. cylindrical wire Harp and flat screens); therefore, for the current study we used Juvik FG measurements. Data from EC tower were available at 30-min intervals; meanwhile, fog, rainfall, and meteorological data were continuously recorded at 5-min intervals. The current study analyzed data from September 2017 to February 2019.

4.2.2 Classification of days according to precipitation type

Data were aggregated at daily timescale. With information from the Juvik FG and the LPM, we determined fog and rainfall inputs. Based on field campaigns, we know that whenever fog was present without another type of precipitation (e.g., drizzle or rain), data were recorded only by the FG and not by the LPM nor the RG. Then, considering fog and rainfall distribution along the day, days were classified into five categories: a) Dry-days, with no precipitation; b) Foggy-days, with fog only presence along the day and no rainfall, which represent the criteria of fog-only events (FO) described in chapter 2 and chapter 3; 3) Fog-dominant days, with fog and rainfall occurrence, but the total fog amount along the day was >50% in comparison with the total rainfall amount, which represent the criteria of fog-dominant events (FD) described in chapter 2 and chapter 3; 4) Rain-dominant days, with fog and rainfall occurrence, but the total rainfall amount along the day was >50% in comparison with the total fog amount; 5) Rainy-days, with rainfall presence along the day and no fog.

4.2.3 Evapotranspiration and meteorological variables interactions under fog and fog-free conditions

Evapotranspiration (ET) values were obtained from the method EC and derived from the air density, vertical wind speed and water vapor mixing ratio; as described in Carrillo-Rojas et al. (2019). To understand to what extent fog occurrence is related to relatively low ET rates in páramo tussock grasses, we estimated ET from Dry-days to determine reduction in ET amounts, when fog and rainfall were present. A comparison between ET from Dry-days and ET from the other four categories aforementioned was performed to observe fog and rainfall influence during some of those days through line-plots.

We analyzed what type of characteristics (e.g., meteorological variables and the time of the day at which fog and rainfall occurs) reduced ET. Using these data, we generated boxplots. In addition, a multiple linear regression model was performed to find whether the meteorological variables are linearly related to ET. Net radiation, relative humidity, wind speed, temperature, vapor pressure deficit and dew temperature were determined as independent variables and ET was set as the dependent variable.

4.2.4 *Inter-annual evapotranspiration variability due to fog and rainfall*

ET daily averages for each month were obtained, to assess variation between Dry-days and days with fog and rainfall presence. Then, we plotted the estimated reduction in ET of Foggy-days, Fog-dominant, Rain-dominant and Rainy-days at monthly basis.

An estimation of total reduction on ET per year due to fog was calculated by multiplying the number of foggy-days and ET difference (average difference between dry-days and foggy-days), and divided by the number of days of this study. The same was calculated for the other day types.

4.3 Results

4.3.1 *Classification of days according to precipitation type*

The distribution of the different day-types throughout the study period (September 2017 – February 2019) is presented in Table 4.1. Out of 546 observed days, 67 days (12.3%) were dry days. Periods of consecutive dry-days were observed during this analysis, with a maximum spell of 5 consecutive dry-days and a mean of 2 consecutive dry-days. It is apparent from this table that 17 days (3.1%) were reported as foggy-days; the occurrence of these type of days were sporadic with only two consecutive foggy-days. The fog-dominant days on average occurred consecutively during three days, with a maximum of 11 consecutive fog-dominant days. The most common type of day in páramo by far, was rain-dominant. A period of 21 consecutive rain-dominant days was reported as maximum and 5 consecutive rain-dominant days on average. Finally our results showed a maximum period of 6 consecutive rainy-days and a mean of 3 consecutive rainy-days at our study site.

Table 4.1.Days of occurrence, average and maximum daily amounts of fog and rainfall for the five types of days.

Day-type	Occurrence (days)	Occurrence %	Fog mean (mm/day)	Fog maximum (mm/day)	Rainfall mean (mm/day)	Rainfall maximum (mm/day)
Dry	67	12.3	0	0	0	0
Foggy	17	3.1	0.3	1.6	0	0
Fog-dominant	111	20.3	4.3	20.9	1.2	6.6
Rain-dominant	279	51.1	2.9	26.4	5.6	37.9
Rainy	72	13.2	0	0	1.3	13.1

4.3.2 Evapotranspiration and meteorological variables interactions under fog and fog-free conditions

Differences in ET can be seen in Figure 4.1, as an example of some specific days of fog, fog-dominant, rain-dominant and rain. From this data, we can see that the highest ET difference during the daytime course resulted with fog-dominant presence (e.g., October 2017), and the smallest difference with fog only occurrence (e.g., October 2018).

Table 4.2 provides the daily averages of ET and meteorological variables for each day-type. The daily average ET for dry-days with standard deviation was 4.9 ± 1.1 mm. On average during fog-dominant days daily ET decreased around 43%, rain-dominant showed a decrease in daily ET of 39%, rainy-days showed a daily ET decrease of 27% and during foggy-days the daily ET decreased only 6%. Except for fog-dominant day the rest of the day-types, showed a temperature almost constant ~6°C, and wind speed varied between 3 – 3.5 m/s. From these data we can infer that ET variation for foggy, rain-dominant and rainy-days is related with fog and rainfall presence rather than temperature or wind speed variability. On the other hand, during fog-dominant and rain-dominant days, relative humidity had the highest mean value over 93%, whereas during foggy and dry-days the relative humidity was below 80%. Vapor pressure deficit (VPD) and net radiation showed the lowest mean values during fog-dominant and rain-dominant days with 0.8, 07 hPa and 98.5, 96 W/m ^{2} respectively.

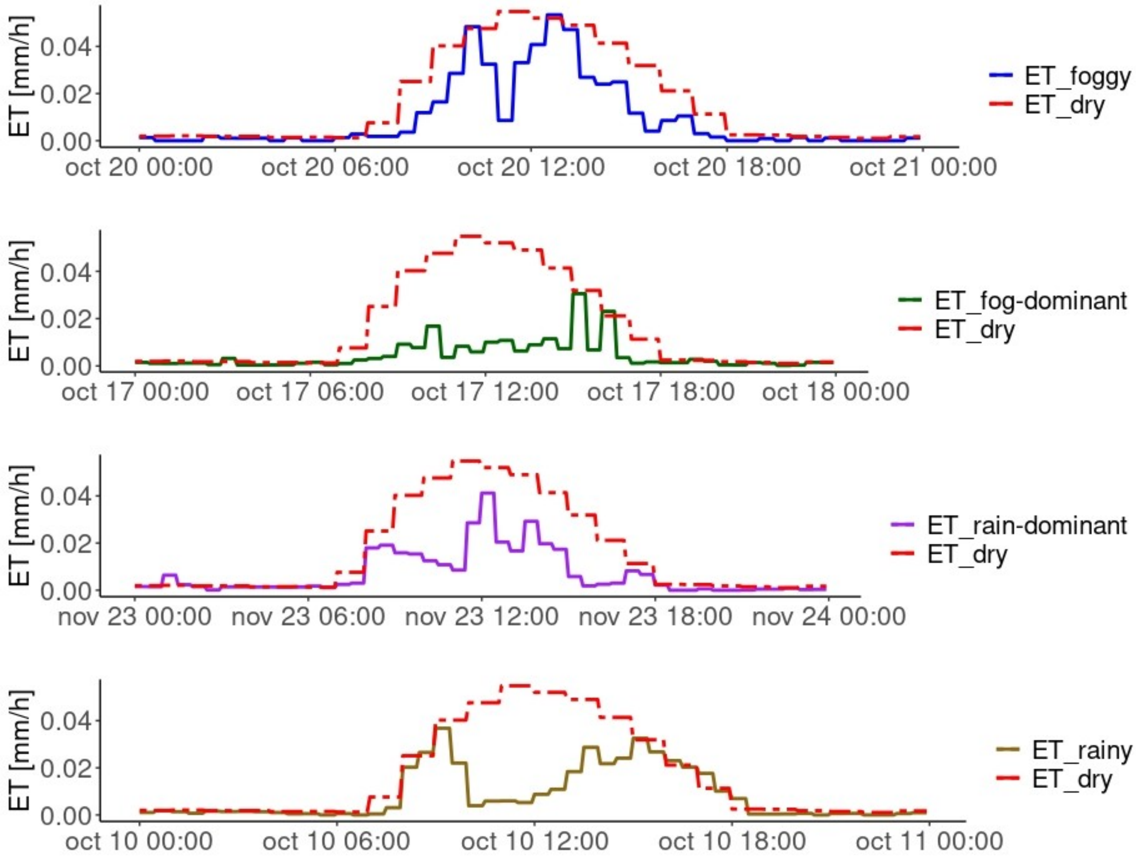

Figure 4.1: Some examples of ET daytime course during conditions of fog and rainfall, compared with average daily ET of dry-days. Foggy day (2018-10-20), fog-dominant day (2017-10-17), rain-dominant day (2017-11-23) and rainy-day (2018-10-10).

Table 4.2.Daily averages of evapotranspiration (ET) and meteorological variables according to day-types.

Day-type	ET (mm/day)	Temperature (°C)	Relative Humidity (%)	Wind speed (m/s)	Vapor Pressure Deficit (hPa)	Dew Temperature (°C)	Net Radiation (W/m^2)
Dry	4.9	6.4	77.1	3.5	2.5	2.5	147.2
Foggy	4.6	6.3	79.0	3.2	2.0	3.3	133.6
Fog-dominant	2.8	5.6	93.1	4.4	0.8	4.7	98.5
Rain-dominant	3.0	6.2	93.2	3.0	0.7	5.5	96.0
Rainy	3.6	6.1	88.5	3.5	1.4	4.3	112.3

Figure 4.2 depicts the daily ET, net radiation, temperature, relative humidity, wind speed, VPD and dew temperature values by boxplots. Minimum values of ET during fog-dominant and rain-dominant days ranged between 0.5-0.9 mm/day and maximum values over 6 mm/day. From these

data we can infer that diminished ET during fog-dominant and rain-dominant days are complementary with climatic conditions like low net radiation and VPD, and high relative humidity. In contrast, ET is not suppressed during foggy-days, and associated climatic conditions are low relative humidity and high net radiation.

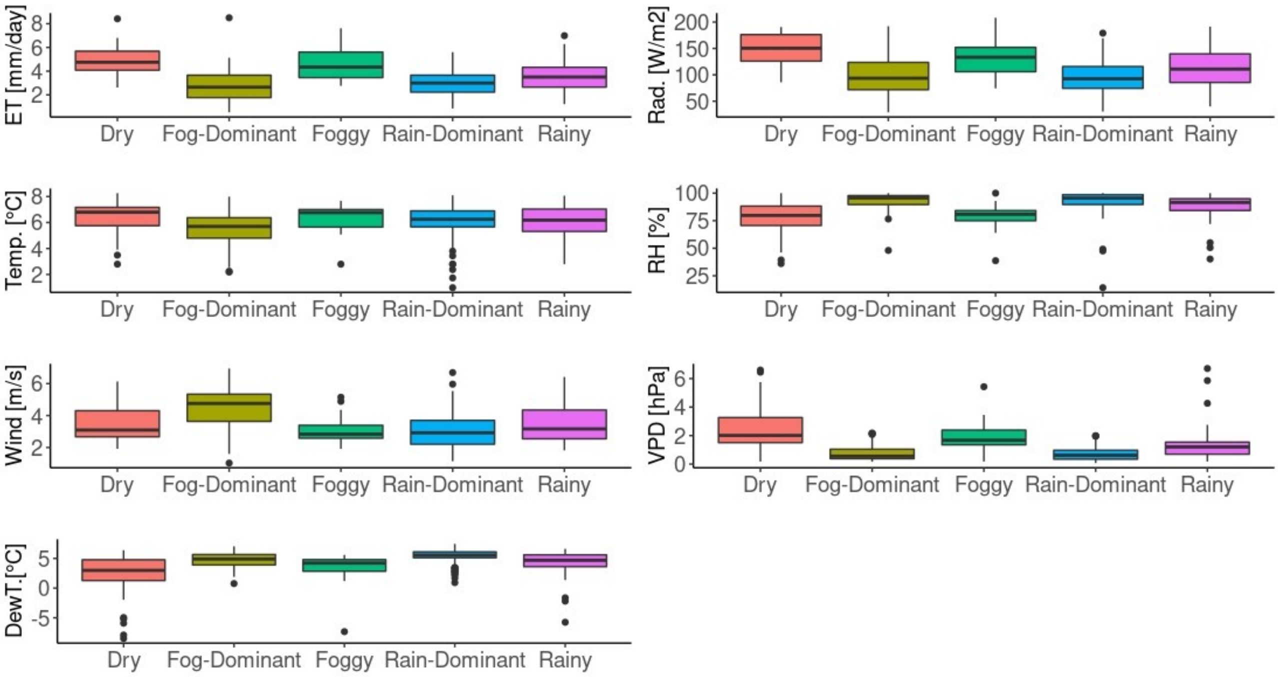

Figure 4.2: Boxplot comparison of ET and meteorological variables according to day-types.

Fog, rainfall and all of the meteorological variables were tested for correlation and multiple linear regression model (see Appendix B). A strong correlation coefficient was observed between ET and net radiation (0.88), while the other variables showed lower coefficients or no association. In addition, before generating a multiple linear regression model we first performed a visual check of model assumptions. Temperature, VPD and dew temperature indicated potential collinearity issues; therefore we did not consider the last two variables for the model. From this analysis, we observed that net radiation, wind speed, relative humidity, fog and rainfall had an statistically significant relationship with ET (see Appendix B). The residual standard error was 0.59 and the coefficient of determination was 0.8.

Fog, rainfall and ET were plotted during the daytime course for dry, foggy, fog-dominant, rain-dominant and rainy-days (see Appendix B). During foggy-days, a decrease in ET was not relevant, since fog was present mostly during early morning hours (from 1 a.m to 6 a.m) with a mean value of 0.12 mm/h and 0.4 mm/h maximum. In daylight hours (9 a.m. to 5 p.m.) when ET reaches higher values fog was intermittent, and with a mean value of 0.2 mm/h and 0.8 mm/h maximum. In contrast, in rainy-days, rainfall showed a high variability along the day (as low as 0.05 mm/h and some as high as 8.6 mm/h), producing a reduction in ET.

Figure 4.3 shows the hourly distribution of ET, fog and rainfall, along the day for fog-dominant and rain-dominant days. It can be seen that fog and rainfall are very frequent together almost every hour, and particularly they are present around noon when ET would reach its higher values. During fog-dominant days (Figure 4.3a), fog presence is higher than rainfall between 1 a.m. and noon, and the rest of the day rainfall prevails. On the other hand, during rain-dominant days (Figure 4.3b) rainfall exceeds fog occurrence earlier (10 a.m.).

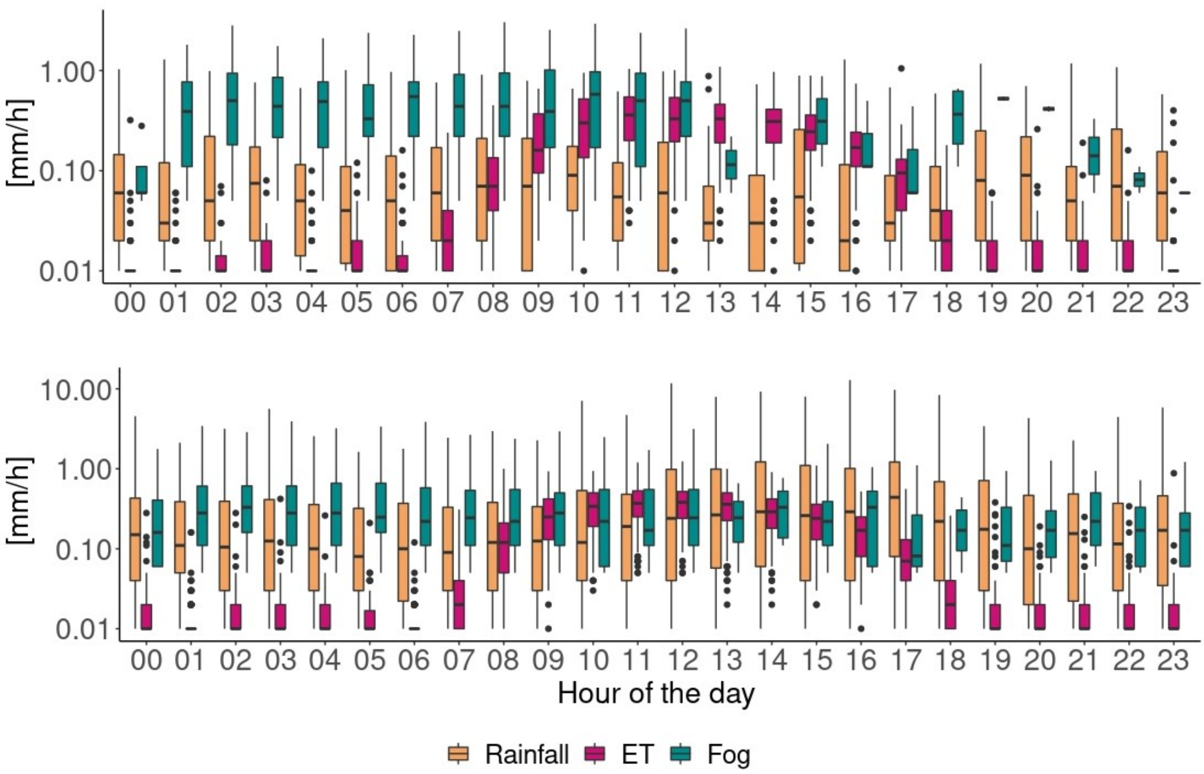

Figure 4.3: Boxplot comparison of ET, fog and rainfall at hourly basis. Y axis scale was converted to log 10. a) Fog-dominant days, b) Rain-dominant days. Black dots are outliers of the boxplot which are outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile.

4.3.3 Inter-annual evapotranspiration variability due to fog and rainfall

ET was calculated at a daily timescale and averaged for each month. Figure 4.4 displays the reduction on ET, from September 2017 to February 2019, for foggy, fog-dominant, rain-dominant and rainy-days in comparison with the average monthly ET for dry-days. In general, December 2017 and October-November 2018 had more foggy days than the rest of the year. For the other months –which fog occurred— at least one day was foggy. The highest reduction on ET during foggy-days occurred in January 2019 with 1.4 mm/day and the lowest reduction took place in September 2017 with 0.4 mm/day. For fog-dominant days a reduction on ET of 3.04 mm/day resulted in July and October 2018, whereas the lowest reduction occurred in February 2018 with 0.2 mm/day. For rain-dominant days a reduction on ET of 2.6 mm/day resulted in August 2018 while the lowest reduction on ET resulted in February 2018 with 1.2 mm/day. Rainy-days did not occur during July 2018 and January 2019, the highest reduction on ET for rainy-days occurred in April 2018 with 2.4 mm/day and the lowest reduction on ET occurred in October 2017 with 0.5 mm/day.

An estimation of reduction on ET per year, was calculated during the different day-types occurrence. The highest estimated ET reductions amounted to 347.8 and 152.9 mm/year due to rain-dominant and fog-dominant days, respectively. In contrast, the lowest estimated ET reductions resulted in 59.6 mm/year and 2.9 mm/year due to rainy and foggy-days, respectively.

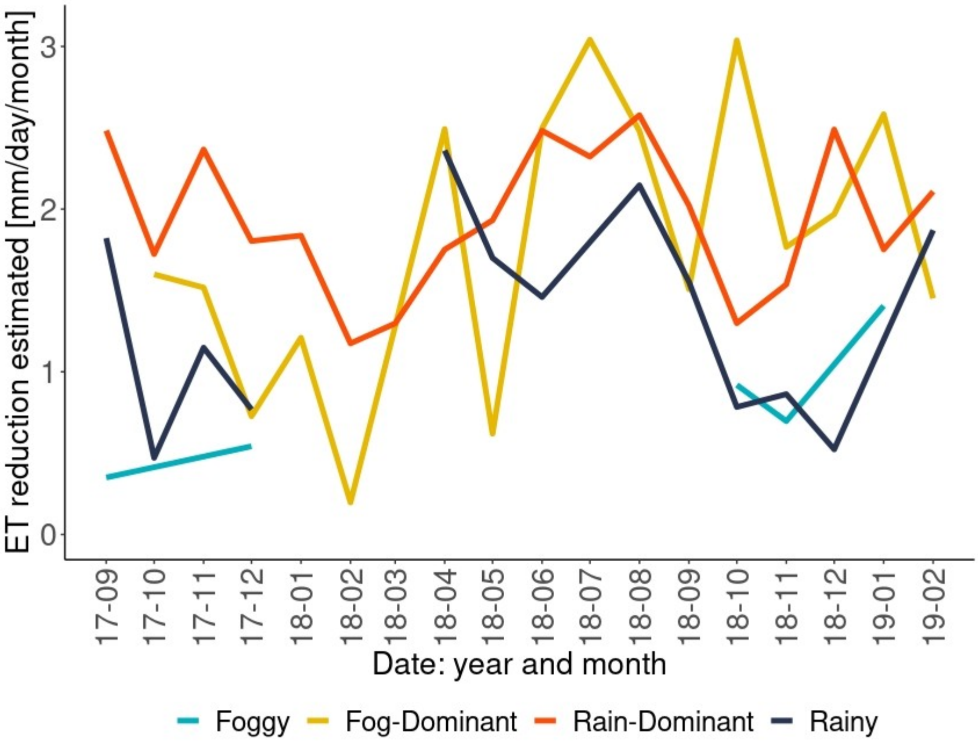

Figure 4.4: Reduction on evapotranspiration (ET) during foggy, fog-dominant, rain-dominant and rainy-days per month. Discontinued lines in foggy and rainy-days mean that no reduction on ET occurred.

4.4 Discussion

4.4.1 Classification of days according to precipitation type

This study found that fog in the Andean páramo is very frequent (Table 4.1), with an overall occurrence of ~75% during the study period (546 days in total). We identified few dry days, and our results are in agreement with Padrón et al. (2015) and Buytaert et al. (2006) who reported low percentages of dry days (< 20%) throughout the year in the south Ecuadorian Andes. Similarly, in the Colombian páramo of Chingaza, Cárdenas et al. (2017) reported 18% of days per year without rainfall and 16% without fog. Moreover, only 3% of the days were reported as foggy-days with fog-only presence and no other type of precipitation. In the páramo, fog-only days occurrence was scarce, since it was regularly combined with other types of precipitation, mainly with drizzle and light rain (Berrones et al., 2021). Only 13% of the days were reported as rainy and without fog. While over 74% of the days fog occurred together with light precipitation. This corroborates that in the páramo, the low-intensity rainfall is very common. For this reason, the knowledge of fog and low intensity rainfall dynamics, through high resolution monitoring, is critical for better understanding the hydrology of this mountain ecosystem, particularly about its ecohydrological processes.

4.4.2 Evapotranspiration and meteorological variables interactions under fog and fog-free conditions

Differences in daily ET were found between dry days, and days with both fog and rainfall at our study site. As shown in Table 4.2, higher reductions in daily ET were observed during the fog-dominant days (43%) and rain-dominant days (39%). Contrary to expectations, this study did not find a substantial reduction on daily ET (6%) due to fog-only presence. This is plausible given that in days with only fog (and not rain) presence, fog inputs were low and because fog mainly occurred in the early morning (see Appendix B) when ET values are low. This outcome is contrary to that of Tobón (2021), who found that in Colombian tropical Andean cloud forest, ET was reduced in average 63%, during foggy days. Between these two Andean ecosystems we have found a substantial difference and variations might be explained due to fog density and the distinct vegetation composition, since the main vegetative controls on ET include leaf and canopy characteristics, regulation of stomata and rooting dynamics (Fisher et al., 2011). The most obvious finding that emerged from the analysis is that the presence of fog combined with other precipitation (e.g. drizzle, light rain and rain) is substantial within the páramo, allowing to reduce canopy evaporation and transpiration, and maintaining canopy close to saturation.

The weak association of fog-only with ET is interesting but not surprising (see Appendix B and Table 4.2). In the páramo, fog commonly occurs in combination with low-intensity rainfall (Figure 4.3), and according to Padrón et al. (2015) drizzle is observed during 80% of the time that rains; therefore, these combined inputs might increase water on leaves surface causing enhanced direct evaporation from the leaf, which results in reduced transpiration (Katata, 2014). Hence, ET reduction is related to a combination of the continuous occurrence of fog combined with rainfall and meteorological factors discussed later.

Fog reduces incoming solar radiation and our results showed that net radiation decreased by around 9.2% during foggy days. This result may be explained by the fact that fog occurrence was higher in early morning hours and lower when solar radiation peaks. Small decreases in solar radiation were found by Bittencourt et al. (2019) in a Brazilian montane cloud forest, by Brauman et al. (2010) in

Hawai'i native forests and by Chung et al. (2017) in a coastal California forested site. In contrast, other studies have shown higher solar radiation reduction due to fog, such as Ritter et al. (2008) in a Subtropical Elfin Laurel Forest in Canary Islands by 58%, Beiderwieden et al. (2007) in a subtropical cypress forest in Taiwan by 34%, and Eugster et al. (2006) in a Puerto Rican elfin cloud forest by 48%. Nonetheless, at our study site considerable radiation reductions were observed during fog-dominant days (33%) and rain-dominant days (~35%). According to Brauman et al. (2010) solar radiation is blocked more efficiently by rainfall clouds than foggy conditions; thus, rainfall prevents evaporation better than fog (Berrones et al., 2021).

Higher relative humidity and lower VPD were associated with fog-dominant and rain-dominant days (Figure 4.2), suggesting greater cloudiness. Yet, evaporation and transpiration losses are reduced (Célleri & Feyen, 2009). Wind speed was higher during fog-dominant days; under these conditions cloud water deposition via impaction on vegetation increased. Since cloud droplets are suspended in the air and effectively transported horizontally by wind and atmospheric turbulence (Frumau et al., 2010), larger fluxes are produced. In general, we found that the meteorological factors influencing ET were solar radiation, relative humidity, and wind speed (see Appendix B). This also accords with earlier observations at the same study site by Ochoa-Sánchez et al. (2020).

4.4.3 Inter-annual evapotranspiration variability due to fog and rainfall

Throughout the 17 months of the study period, fog-dominant days occurred at least three times per month, but during June to August we registered 15-20 days per month. In addition, we observed that this period coincided with the less humid months of the study; ET reported their lowest values (Figure 4.4), suggesting that fog presence can inhibit transpiration, limiting the water loss by evaporation and also could alleviate water stress even during less humid periods. According to Ochoa-Sánchez et al. (2020) in the páramo, evaporation contributes more to ET than transpiration; therefore, fog plus rainfall clouds result crucial for the transfer of water to the atmosphere.

Estimated annual ET reductions during fog-dominant and rain-dominant conditions ranged between 153 and 348 mm, suggesting that the presence of these water inputs not only reduce the evaporative demand but also can reach the soil generating changes in soil water content (Berrones et al., 2022). Moreover, to minimize water loss and maximize CO_2 absorption for photosynthesis, plants regulate their stomata (Fisher et al., 2011). Fog might block the pathway of CO_2 and might prevent gas exchange, since the rates of CO_2 assimilation and uptake are strongly related to solar radiation

(Beiderwieden et al., 2007). As fog could be considered as an indicator of changes in plant diversity and functioning among different ecosystems (Aparecido et al., 2018) and considering that páramo vegetation develop at high altitude with cold, wet and windy conditions, further work is still needed to quantify fog contribution to each component of ET in this type of vegetation.

4.5 Conclusions

This study aimed to explore the influence of fog on evapotranspiration (ET) process in the páramo tussock grasses. The following conclusions can be drawn from it:

Foggy days in the páramo were scarce (3% of occurrence) and with no critical impact on daily ET variation (6%). Yet, prevailing fog combined with drizzle, light rain or rain, reduced daily ET significantly by 43% compared with daily ET rates under clear conditions (no precipitation and no fog).

During fog-dominant and rain-dominant days, net radiation diminished ~35% thus allowing ET reductions during the daylight. Mixed conditions of fog and rainfall with meteorological variables such as net radiation, relative humidity and wind speed showed a significant (coefficient of determination of 0.8) influence on low ET rates. Thus, fog and rainfall interactions reduced evaporation, minimizing water losses.

Although fog mainly occurs in the early morning hours, the presence of cloud water in addition with high relative humidity generated an indirect influence on ET reductions. Hence, during daylight hours, both fog and low-intensity rainfall (and its associated cloudy conditions) reduced the evaporative demand.

During less-humid months fog contributed to maintain wet conditions that diminished ET rates. Estimations of ET reductions due to fog and rainfall varied between 153 and 348 mm per year. In the wet Andean páramo fog and low-intensity rainfall occur frequently, and they resulted critical, playing a key role on ecohydrological processes.

This is the first study that has investigated the effects of fog-only and fog-dominant weather conditions on ET rates in the páramo ecosystem; hence, this work offers valuable insights into understanding their implications for vegetation and water resources availability.

Chapter 5

5 Conclusions

5.1 Synthesis

This dissertation has provided a deeper insight into the interactions of fog with ecohydrological processes in the páramo ecosystem, by means of the quantification of fog water, the assessment of its contribution to soil moisture, and the analysis of its impact on evapotranspiration rates.

Several different types of fog collectors, of both active and passive configurations, have been discussed briefly in chapter 2. For our study purposes and climatic conditions within the páramo, we analyzed the advantages and disadvantages of the collectors based on the characteristics of each one, and on findings reported in literature. Despite the passive fog collectors are not specific to fog in situations where fog and wind-driven rain occur simultaneously and their efficiency is dependent on prevailing wind speeds, they are useful instruments for site characterization and used worldwide. Active fog collectors are more expensive, and its instrument maintenance is more complex. Thus, considering the complex topography of our study site, we concluded that the more suitable configurations to measure fog occurrence and to characterize local fog conditions were the described passive fog collectors.

A fog measuring setup, that included three different types of fog gauges (i.e., cylindrical Juvik type, cylindrical wire harp type and flat screens), was designed and installed at the Zhurucay Ecohydrological Observatory to measure fog water. Despite of the difficult meteorological conditions of the wet páramo, we installed the fog gauges complementing the extensive instrument setup that exists at the Observatory and creating a monitoring site never seen before in this ecosystem. It is worth mentioning that we first evaluated how modifications to the gauges such as adding protective covers on top to avoid catching vertical precipitation and a system for automatic registration of collected water (e.g. Texas tipping bucket rain gauges and data loggers connected individually for each fog collector), could give less inaccurate estimates. Moreover, an extensive fieldwork was carried out to assure the correct functioning of the monitoring equipment; in the same way, fieldwork campaigns were executed to observe and characterize the fog occurrence during both daytime and nighttime—including spells of fog events and the measurement of lag time between appearance of fog and its accumulation on the collectors. By using both fog gauges and laser disdrometer data, we could discriminate fog and other types of precipitation during events. In this regard, a key contribution of this research is that we isolated fog from other types of precipitation during the fog occurrence, and consequently we quantified only fog and the distribution of the other types of precipitation while fog takes place.

The instrumental setup worked reliably under the páramo conditions and the data obtained were of high quality. Statistical tests allowed to determine to what extent different passive fog collectors influenced in obtaining accurate estimations of horizontal cloud water fluxes. The assessment of the performance of three different types of passive fog gauges, on an event basis, showed that the cylindrical types outperformed the flat panels. Since in the páramo both wind direction and wind speed are quite variable the use of a single flat panel mounted in a fixed orientation could not record accurate fog amounts; therefore, it was necessary install two flat panels oriented to the two main wind directions; and supplementary corrections for wind direction were required for the use of the flat panels. In contrast, the cylindrical gauges have uniform exposure to all wind directions. From the constructive point of view and considering the convenient installation in the field, the cylindrical fog gauges resulted more feasible. The efficiency of the Juvik gauge was independent of wind speed. The collection efficiency of the flat screens was affected by wind speed and with a minor effect on the wire harp. Among fog gauges, there was a good linear relationship (values ranging from 0.87 – 0.92) comparing the volumes collected by them on an event basis. Calibrations of our equipment, wind direction corrections, and laser disdrometer data to identify other precipitation different than fog, enabled to reduce errors on our estimates. Consequently, we can conclude that in the páramo any cylindrical fog collector is suitable.

In this study, the availability of a high resolution sensor, like the disdrometer for measuring low-intensity rainfall, allowed us to differentiate the rainfall from the fog water through the mean volume diameter characterization. Since the disdrometer is not able to measure tiny droplets of fog water, and at the páramo fog occurs most of the time simultaneously with low-intensity rainfall; the use of this sensor enabled us to characterize and quantify the different types of rainfall present during fog occurrence. Notwithstanding, the limitations of this sensor includes the over estimation of high-intensity rainfall and wind-induced errors, when the sensor is parallel to wind. Since we considered for analyses the characterization of low-intensity rainfall and events with wind speed below 4 m s^{-1}, these drawbacks could not have affected our reported results. A prior study (Padrón et al., 2015) at the same site showed that the disdrometer results a suitable complementary technique for increasing the accuracy of rainfall estimations.

To understand the fog occurrence and variability, data were analyzed on event and hourly basis; fog amounts were categorized under conditions of only fog and fog combined with rainfall. Fog primarily occurred in combination of drizzle and light rain. Fog occurrence was common in the early morning and during the night, and while it was still present at other times of the day, it was less frequent and less intense. The fog-only events were of short duration (< 3 hours) and low intensities (< 0.2 mm h^{-1}), whereas the other fog events were of longer duration but fog intensity not exceeding 1 mm h^{-1}. Average daily fog was estimated around 1.37 mm. Rainfall amounted to 1200 mm/year and on average fog gauges collected a total of 340 mm/year. Given that, within the páramo fog occurs most of the time combined with drizzle, the latter represents the total amount of fog and low-intensity rainfall recorded by the gauges. Cloud water estimates suggest a potential extra water input of 340 mm (22%); however, this input not necessarily reach the ground and the impaction of droplets is also dependent on vegetation features (e.g., type, size and density of the foliage).

In addition, three machine learning algorithms (tree decisions, random forest and clustering) were used to analyze the relationship among some variables (e.g. temperature, wind speed, relative humidity), fog occurrence characterization and prediction (non published results). As air cools temperature drops closer to the dew point, which can be related with fog formation. However, at our study site the temperature showed no relation for fog formation, plausible because fog uplift comes from the lower part of the catchment, then the cooling of air masses occurs during the trajectory. Therefore, temperature resulted not being a specific determinant for fog formation at our study site. On the other hand, analyses of wind speed and relative humidity showed a relationship with fog occurrence, which led us to better understand and interpret the results discussed in the previous chapters.

Since fog is a permanent feature in the páramo, people had the hypothesis that fog directly contributes to stream flow. Therefore, it was very important to understand the magnitude of fog water contribution to soil moisture in the páramo ecosystem. In our case, fog intercepted by vegetation reached the soil only under specific circumstances. During fog-only conditions just 4.5% of the total fog water available in the atmosphere reached the soil, producing changes in soil moisture between 0.1 and 0.2 mm. At least 1 hour was needed for water to reach the soil. These events were characterized by total event amounts of < 5 mm, and event duration between 1 and 8 hours. Notwithstanding events with fog-only presence make a negligible contribution to stream water, their presence contributes to maintain wet conditions for the vegetation. The events with fog and rainfall combined, resulted in a major contribution to soil moisture (as high as 4.3 mm), because of their long duration (averaging over 13 hours) and high total amounts (over 10 mm per event). Clearly, these types of events are potentially important for both soil moisture and stream flow, mainly because of the large proportion of drizzle and light rain. It also was found that none of the meteorological variables (e.g. wind speed, air temperature, dew temperature, vapor pressure deficit, solar radiation, and relative humidity) were linearly correlated with increments on soil water moisture. Hence, the most relevant variables associated with positive soil water changes were the total amount, the duration and the intensity of fog. In this regard, the fog-only input does not feed the streams, plausible because the tussock grasses are not engulfed in cloud cover and fog due to their height.

Another common hypothesis is that fog significantly reduces the amount of evapotranspiration and for this reason the environment remains with a high relative humidity. When compared to clear weather conditions (no precipitation and no fog), our results show that the daily evapotranspiration was reduced by 6% during foggy conditions (fog-only) and by 43% when both fog and rainfall occurred (mixed conditions). The presence of fog affects the incoming solar radiation; thus, less energy is available for biogeochemical processes in foggy conditions. We observed statistically significant relationships ($R^2 = 0.8$) between evapotranspiration and meteorological variables such as net radiation, wind speed and relative humidity, as well as with fog and rainfall amounts. Therefore, the presence of fog and rainfall reduced solar radiation and contributed to maintain a high relative humidity; then, these conditions reduced the evapotranspiration, minimizing the water losses from the ecosystem. In addition, decrements in net radiation were obtained with fog and rainfall occurrence, by 33% under mixed conditions and 9.2% under foggy-conditions. Cumulative annual value of evapotranspiration is about 622 mm and estimations of evapotranspiration reductions due to fog and rainfall combined ranged between 153 and 348 mm per year. We can conclude that (i) the reduction in evapotranspiration due to only fog is much smaller than anticipated (ii) the synergy of fog and rainfall (particularly due to cloudy conditions) significantly reduces evapotranspiration of tussock grasses and (iii) during less-humid months fog was important not only through the addition of water to tussock leaves, but also by inhibiting transpiration and reducing evaporation.

Moreover, the páramo provides a variety of ecosystem services, The regulation of these services are related with the combination of water inputs from rainfall and fog, the high infiltration capacity of soils, and soil water storage; then it is worth to mention the implications of fog on these services and functions. For example, the absence of persistent fog could affect water yield due to an increase in evapotranspiration. Despite the presence of dry periods in the páramo are scarce, the continuous presence of fog might alleviate dry spells; thus, fog becomes an important asset for vegetation functioning. In general, reduced cloud cover and fog presence not only reduce vegetation composition, but increase surface evaporation, resulting in decreased stream flow.

The tropical mountains have been stated as highly vulnerable to climate changes. Climate change scenarios for mountain regions predict an increase in surface temperatures, changes in precipitation regimes and a substantial reduction in fog frequency (Aparecido et al., 2018). For example, some studies have shown that reduction in fog frequency can lead to plant tissue desiccation, which might result in mortality and associated lower canopy interception rates and storage capacities (Foster, 2001). Climate change might affect negatively the base level of clouds causing a loss in contact between fog and vegetation, and for páramo vegetation would be more dramatic, since tussock grasses are shorter. Even land use conversions in lowland parts of catchments could affect the formation and cloud level, which implies a lower contact of clouds with the high mountains; hence, a possible change in precipitation frequency and distribution (Tobón, 2009). Modifications in hydrological cycles and ecosystem degradation in the páramo will impact urban areas that rely on water supply.

Finally, from this study we can conclude that fog and low-intensity rainfall (mainly drizzle) are key factors for ecohydrological processes of the páramo; its importance mainly lies in the influence on water inputs and outputs. This study aimed at contributing to the understanding of the role of fog in the páramo and this is the first time that fog has been studied with such detail. Although much progress has been made in learning fog relevance to the ecosystem, there is still work to be done, which is described in the following section.

5.2 Future Research

The Andes mountains are of great importance for providing water for lowlands. However, they are vulnerable and fragile. Due to its topography and geophysical diversity, climatic and land use changes can impact the hydrology of these ecosystems. The findings in this dissertation identified new challenges and opportunities for future investigations that are remarked in this section.

This dissertation highlighted among other things the difficulty to isolate fog from the low-intensity rainfall; however, the use of high-resolution data (i.e. laser disdrometer) allowed to do detailed analyses of the precipitation types. Given that the contribution by fog-only to total water input proved rather small, measurements of fog combined with low-intensity rainfall should be considered as a whole for analyses. As precipitation is an important input for hydrological modeling, the approach should include both the cloud water and rainfall to derive better estimations. The quantification of fog water, its contribution to soil moisture and the impacts on evapotranspiration were performed for the tussock grasses, the most common vegetation of the páramo. However, Polylepis forest are also a common feature in the páramo; therefore, further studies are necessary to interpret the importance of fog on its ecohydrological functioning.

Fog deposition has been recognized as an important asset for ecohydrological processes; despite the amount of fog water reaching the soil is low, it still has an effect on plants functioning via foliar uptake and by suppressing leaf water loss to the atmosphere. The stable isotopes of water (^{2}H, $^{18}0$) extracted from plant material can indicate the sources of water used by plants (Brunel et al., 1995). Thus, the stable isotopes technique could be useful to establish transport pathways of fog within the páramo vegetation. In addition, it was beyond this PhD research to test the origin of fog water through the stable isotope method; thus, it is still unexplored whether fog originates from direct re-evaporations at the lower part of the cloud forests or from the continental air masses.

Increasing temperatures and changes in precipitation patterns predicted by climate change scenarios would affect directly the water cycle. In addition fog has a strong influence on energy balance (Price, 2019). It has been discussed that fog and low-intensity rainfall are directly related with low evapotranspiration rates, mainly due to incoming solar radiation reductions. Since climate models project substantial reductions in fog frequency in mountain regions (Aparecido et al., 2018), fog reductions not only might affect vegetation functioning, but also ecosystem functioning; therefore, it is necessary to address the impact of these changes. In the páramo, the knowledge of fog dynamics and the understanding of its effects on ecohydrological processes is relatively new. To assess climate change scenarios or to predict fog occurrence long-term, data is required. Machine learning techniques would be useful to this approach.

At our study site, fog did not show spatial variability due to the catchment topography and size. However, fog could vary since it is not a continuous phenomenon. To analyze its variability at catchment scale it is necessary to consider the thermal gradient, the micro meteorology of the lower part of the catchment, and the distribution of clouds to design a suitable setup that is representative.

It is still unexplored the impact of large-scale phenomena occurring within the Earth system at different timescales such as El Niño Southern Oscillation, La Niña events, etc., on the contribution of low-intensity rainfall like fog. Therefore, it is necessary a long term data collection to address this research question. Satellite observations can be used for fog detection, however field observations are essential for verification purposes.

Taking advantage of high-resolution data, droplet size spectra and liquid water content information,numerical forecast models can be used for fog forecasting. However, to develop accurate forecasting models it is necessary a better understanding of fog microphysics and the large/small scale effects on its formation (Gultepe et al., 2009). Also, numerical models can be used for estimating fog water deposition, to understand how fog would be related to carbon and nitrogen cycles in the páramo ecosystem.

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Appendix A

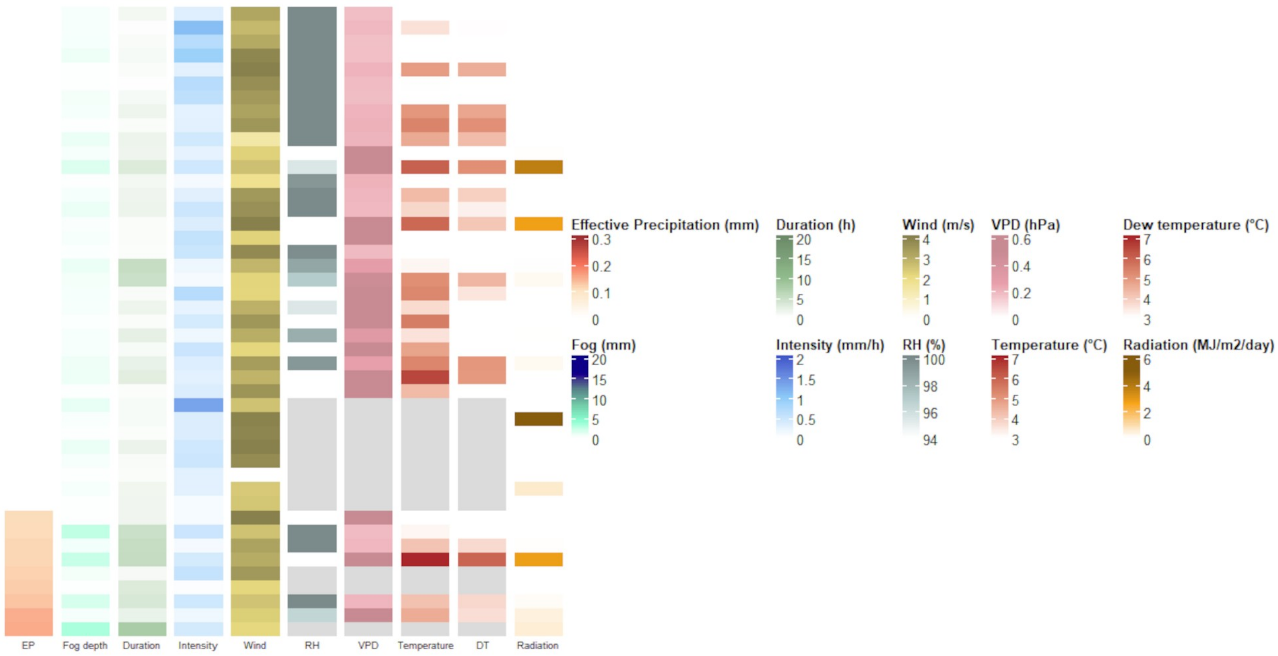

Figure A: Heat-map for fog-only events as they relate to effective precipitation, the event characteristics, and the meteorological variables (wind, relative humidity, vapor pressure deficit, temperature, dew temperature, and radiation) analyzed to find an influence on soil moisture gain. Each bar represents a FO event and they are organized by effective precipitation increasing values.

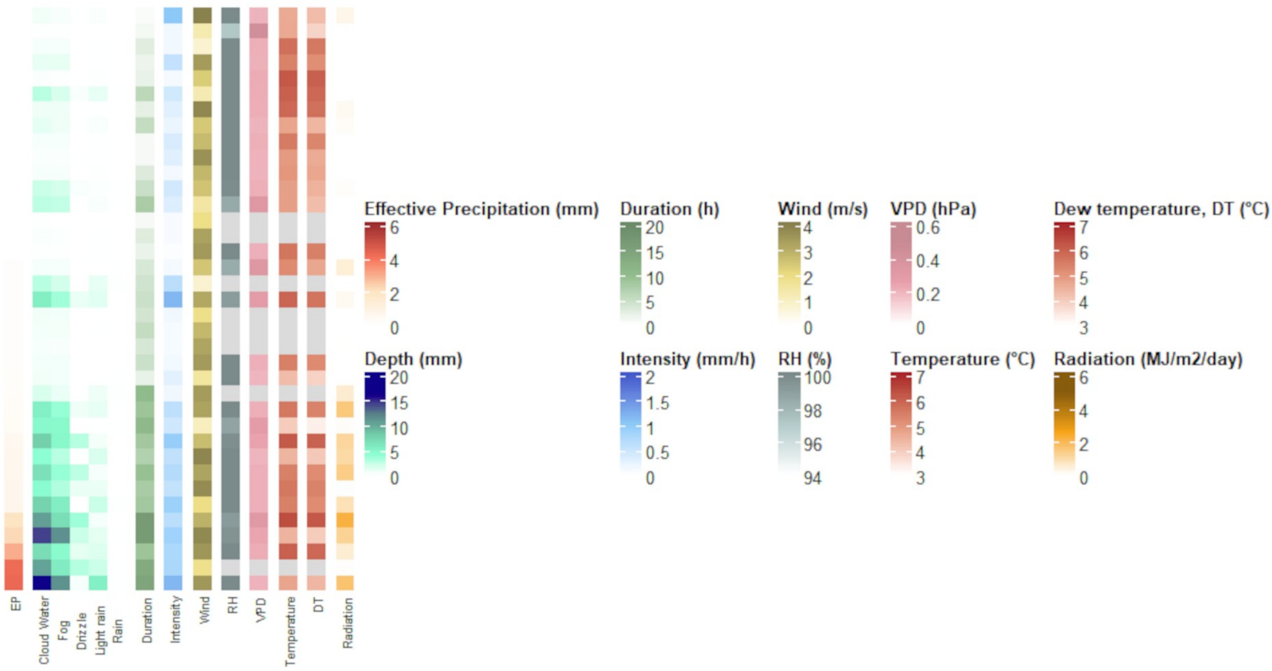

Figure B: Heat-map for fog-dominant events as they relate to effective precipitation, the event characteristics, and the meteorological variables (wind, relative humidity, vapor pressure deficit, temperature, dew temperature, and radiation) analyzed to find an influence on soil moisture gain. Each bar represents a FD event and they are organized by effective precipitation increasing values.

Appendix B

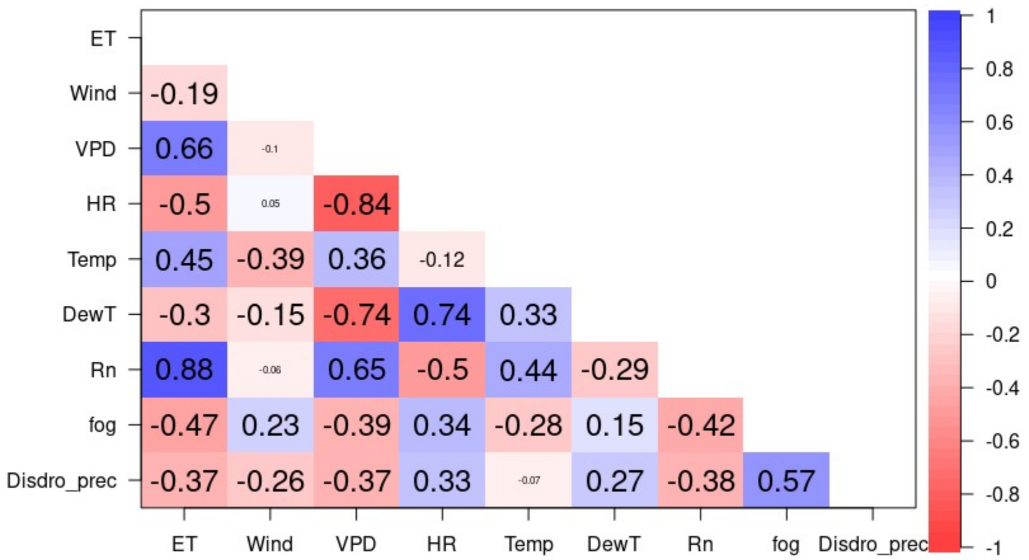

Figure C: Correlation among fog, rainfall, and meteorological variables with ET (evapotranspiration). VPD = vapor pressure deficit; HR = relative humidity; Temp = temperature; DewT = dew temperature; Rn = net radiation; Disdro_prec = rainfall.

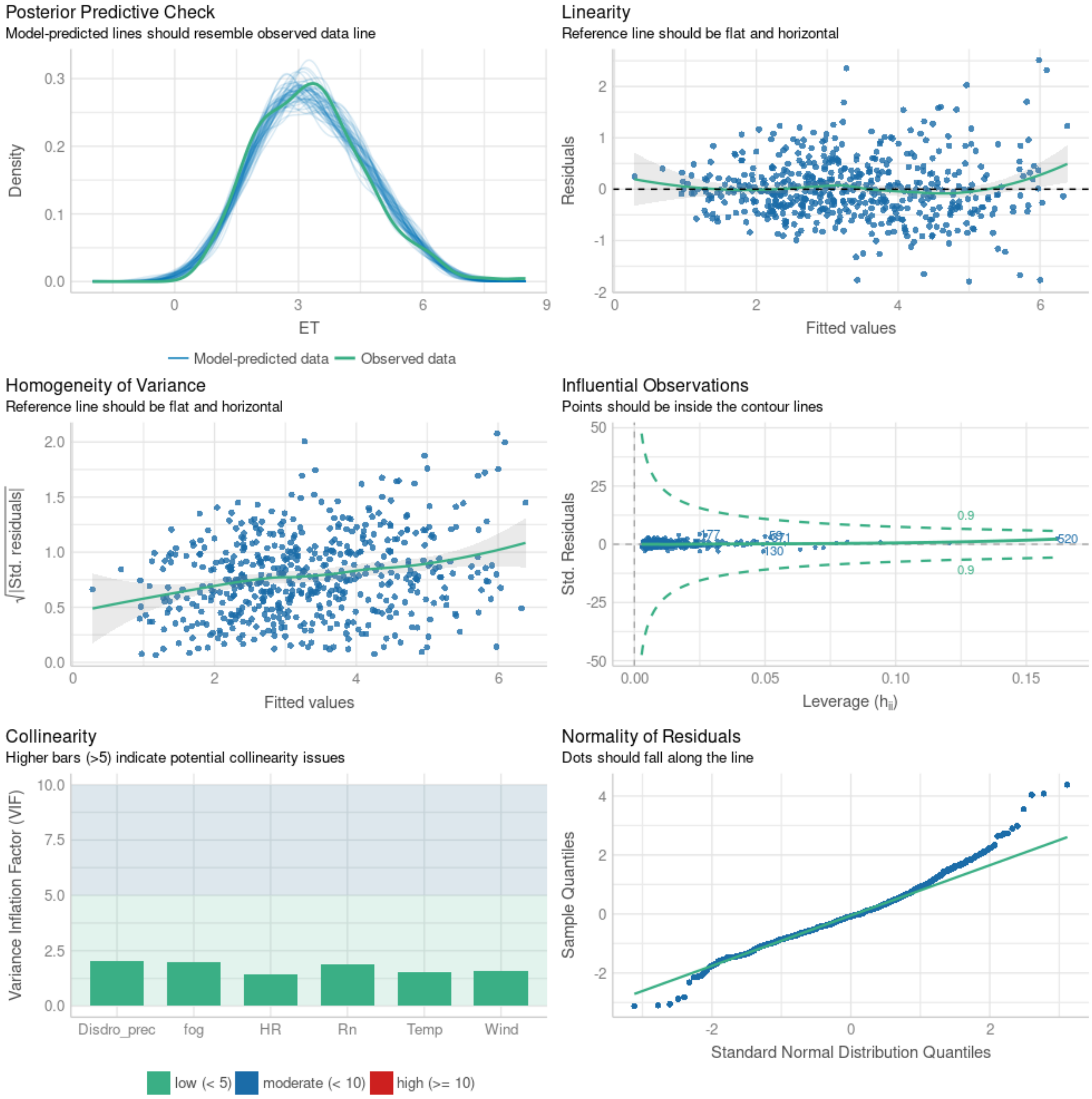

Figure D: Conditions of application for the multiple linear regression model. Vapor pressure deficit and dew temperature were not considered due to potential colinearity issues. Disdro_prec = rainfall; HR = relative humidity; Rn = net radiation; Temp = temperature.

Table A: Multiple linear regression model

	Estimate	Standard Error	t value	Pr(>|t|)
Intercept	1.3064483	0.3239840	4.032	6.32 e-05 ***
Net radiation	0.0290503	0.0009519	30.517	< 2e-16 ***
Wind speed	-0.1422702	0.0255411	-5.570	4.02e-08 ***
Relative Humidity	-0.0076081	0.0027302	-2.787	0.00551 **
Fog	-0.0157636	0.0093045	-1.694	0.09080 .
Rainfall	-0.0159907	0.0072156	-2.216	0.02710 *
Temperature	0.0311630	0.0278206	1.120	0.26315

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

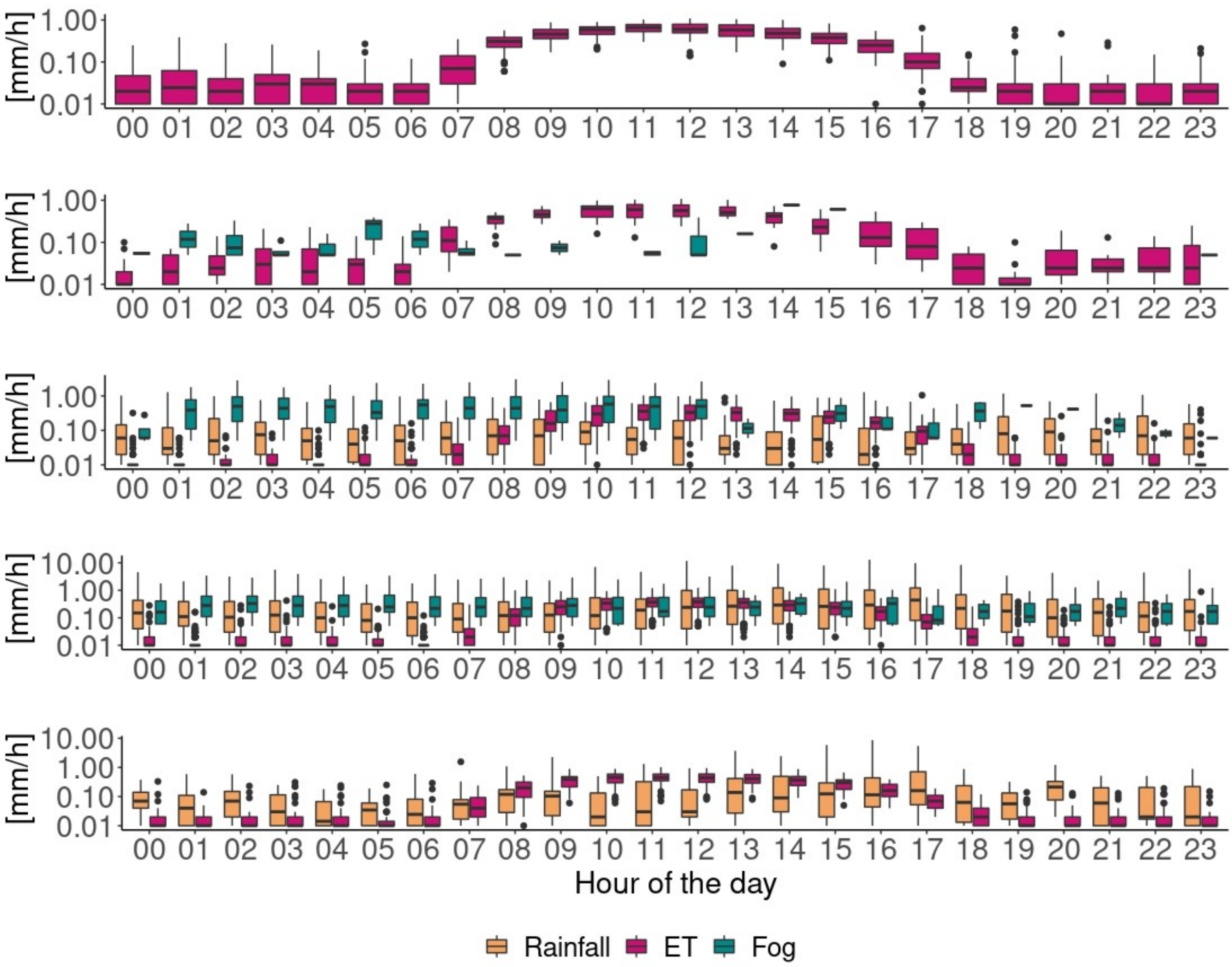

Figure E: Fog, rainfall and evapotranspiration at daily basis for each of the day-types. For a better visualization y-axis was converted to log 10 scale. a) Dry-days, b) Foggy-days, c) Fog-dominant days, d) Rain-dominant days, and e) Rainy-days.

About the author

Gina Marcela Berrones Guapulema was born in Riobamba, Ecuador on October 30th, 1982. She graduated as Agricultural Engineer from the Faculty of Natural Resources, at the Escuela Superior Politécnica of Chimborazo, Riobamba – Ecuador in 2007. She graduated in 2011 as Master of Science in Water Resources at the Southern University of Chile, Valdivia – Chile. From 2012 to 2016, she worked as assistant professor at the University Tecnológica Equinoccial, Quito – Ecuador, and as consultant in agricultural projects. In 2017, she started the Doctoral Programme in Water Resources at the University of Cuenca.

Peer Review Publications

◦ Berrones, G., Crespo, P., Carrillo-Rojas, G., & Célleri, R. (2022). Fog and rainfall influence on evapotranspiration variability in the Andean páramo tussock grasslands. *Journal of Mountain Science* (in review)

◦ Berrones, G., Crespo, P., Ochoa-Sánchez, A., Wilcox, B.P., & Célleri, R. (2022). Importance of Fog and Cloud Water contributions to Soil Moisture in the Andean Páramo. *Hydrology* 9 (4), 54; https://doi.org/10.3390/hydrology9040054

◦ Berrones, G., Crespo, P., Wilcox, B. P., Tobón, C., & Célleri, R. (2021). Assessment of fog gauges and their effectiveness in quantifying fog in the Andean páramo. *Ecohydrology*, e2300(April). https://doi.org/10.1002/eco.2300

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Conferences

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3 Scientific writing, 2017.
4 Water Resources Planning and Management, 2017.
5 Scientific oral and poster presentations, 2017.
6 Prediction of hydrological and meteorological variables: Models based on decision trees with R, 2018